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SOILS AND GRASSLAND TYPES OF THE SERENGETI PLAIN (TANZANIA)

Their distribution and interrelations.

Part I: Nature of the study, methods and general information

Part II: Soils of the Serengeti Plain and their characteristics

H.A. de Wit

Soils and grassland types of the Serengeti Plain (Tanzania). Their distribution and interrelations.

Proefschrift
ter verkrijging van de graad van
doctor in de landbouwwetenschappen,
op gezag van de rector magnificus,
dr. H.C. van der Plas,
hoogleraar in de organische scheikunde,
in het openbaar te verdedigen
op vrijdag 16 juni 1978 des namiddags te vier uur
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(Communications Agricultural University Wageningen, The Netherlands)

Aan mijn ouders

Aan Annemarie

Stellingen

I

De opvatting dat de bodems in het "Long grassland" van de Serengeti Plain ontstaan zouden zijn uit een kalkrijk conglomeraat en niet -zoals de overige gronden van de Serengeti Plain- uit vulkanische as, is onjuist.
G.D.Anderson & L.M.Talbot (1965), J.Ecol.53 : 33-56.
(Dit proefschrift)

II

De zwak ontwikkelde bodemprofielen in het "Short grassland" van de Serengeti Plain zouden, ondanks hun te hoge volumegewicht, in het Amerikaanse bodemclassificatiesysteem ingedeeld moeten kunnen worden bij de suborde der Andepts.
Soil Taxonomy (1975), U.S.D.A., Agric.Handbook 436.
(Dit proefschrift)

III

Bij de uitwerking van de orde der Mollisolen in Soil Taxonomy is onvoldoende rekening gehouden met Mollisolen die in tropische gebieden voorkomen.
Soil Taxonomy (1975), U.S.D.A., Agric.Handbook 436.
(Dit proefschrift)

IV

In semi-aride gebieden vormen vegetatiegrenzen -in tegenstelling tot hetgeen geponeerd door De Meester- een bruikbaar hulpmiddel bij het vaststellen en in kaart brengen van verschillen in bodemgesteldheid.
T.de Meester (1971), Agric.Res.Rep.752, Wageningen.

V

De conclusie van Anderson & Talbot dat bij de gebleken preferentie ten aanzien van het gebruik van het "Short grassland" van de Serengeti Plain door de migrerende kudden herbivoren de minerale samenstelling van het grasgewas geen rol speelt, is strijdig met de resultaten van Kreulen.
G.D.Anderson & L.M.Talbot (1965), J.Ecol.53: 33-56.
D.A.Kreulen (1975), E.Afr.Wildl.J.13: 297-304.

VI

Aan de door Bell en McNaughton beschreven successie in begrazing van een aantal graslandtypen in het Serengeti National Park door de belangrijkste migrerende diersoorten mag geen ecologisch principe worden ontleend; de bij deze successie optredende voordelen in voedselaanbod voor sommige van deze diersoorten zijn slechts van incidentele aard en gelden maar voor een beperkt aantal graslandtypen.
R.H.V.Bell (1971), Sc.Am.224 : 86-93.
S.J.McNaughton(1976),Science 191 :92-94.

VII

Bij de inrichting van wildparken in ontwikkelingslanden dienen -in tegenstelling met hetgeen in de praktijk blijkt voor te komen- de landbouwkundige mogelijkheden in de daartoe bestemde gebieden tevoren zorgvuldig te zijn onderzocht.

VIII

Het onderscheiden van soorten binnen de geslachten Salicornia en Microcnemum (Chenopodiaceae) op grond van de kleur van de plant of plantedelen dient vermeden te worden.
Zie: P.H.Davis (1967), Flora of Turkey and the East Aegean Islands, Vol II : 321-324.

IX

Om misverstanden over de verzoutingstoestand van het Rijnwater te voorkomen, dient de mate van verzouting te worden weergegeven in eenheden van geleidbaarheid of concentratie en niet -zoals in de berichtgeving gebruikelijk is- in eenheden van gewicht die per tijdseenheid door de rivier worden afgevoerd.

X

De vangsten, het afgelopen jaar in de Rijn door sportvissers in de omgeving van Wageningen gedaan, zijn niet te rijmen met het in de landelijke pers herhaaldelijk gebezigde begrip van dode rivier.

XI

In verband met de sterke stijging van het aantal huiskatten in Nederland verdient het aanbeveling een belasting op het houden van deze diersoort in te voeren.

Proefschrift van H.A.de Wit
Soils and Grassland Types of the Serengeti Plain (Tanzania). Their distribution and interrelations.

Korte samenvatting

De Serengeti Plain maakt deel uit van een zeer oude versneden hoogvlakte die tijdens het Pleistoceen overdekt is door aeolische afzettingen van vulkanische assen met een sterk alkalisch karakter; de assen waren afkomstig van de Ngorongoro Highlands.
Het klimaat is semi-aride en wordt gekenmerkt door een droge en natte tijd. De jaarlijkse neerslag varieert van ca 400 mm in het zuidoostelijk tot ca 800 mm in het noordwestelijk deel van de Serengeti Plain. Lokale verschillen in regenval in combinatie met de bijzondere aard van het moedermateriaal hebben geresulteerd in een aanzienlijk aantal verschillende bodemtypen met bijzondere eigenschappen zoals thixotropie, hoge omwisselcapaciteit van de kleifracties, hoge zoutconcentraties in vele profielen, vorming van calcic en petrocalcic horizonten.
De Serengeti Plain is bedekt door grasland waarin vrijwel geen bomen voorkomen. Binnen het grasland kunnen, op basis van de graslengte en botanische samenstelling, 3 hoofdzones worden onderscheiden, te weten het zogenaamde korte, halflange en lange grasland.
De grenzen van deze hoofdzones bleken in grote lijnen overeen te komen met die tussen drie belangrijke, zogenaamde bodemlandschappen.
In de hoofdstukken 2.1, 2.2 en 2.3 van deel II zijn een aantal bodemeigenschappen zoals textuur, structuur, physische en chemische eigenschappen van de gronden binnen de drie bodemlandschappen uitvoerig beschreven. Uit de overzichten is gebleken dat de factor regenval van zeer grote invloed is op de bodemgesteldheid; samenhangend met de verschillen in regenval blijken gronden in het zuidoosten lemig, zwak ontwikkeld, zout en alkalisch en kalkrijk te zijn; in het noordwesten zijn de gronden kleiig, minder zout en alkalisch en tot flinke diepten ontkalkt en vertonen een sterke profiel ontwikkeling.
De factoren verzouting (mate en type) en alkaliteit bleken van grote invloed op de botanische samenstelling van het grasland te zijn. Naast belangrijke regionale verschillen -zoals bijvoorbeeld tussen de drie bodemlandschappen- komen veelvuldig belangrijke verschillen in de verzoutingstoestand op korte afstand voor, waarbij de ligging van de betreffende profielen binnen een toposequentie van groot belang bleek. Binnen de drie hoofdzones van het grasland worden dan ook velerlei patronen aangetroffen. Een veel voorkomend patroon is dat van scherp omgrensde plekken van langere en kortere grassen of van graslandtypen met een hoge bedekkingsgraad of een lage bedekkingsgraad. De mate van verzouting en/of alkaliteit van de ondergrond bleek hier duidelijk gecorreleerd met genoemde patronen:

kort gras en/of lagere bedekkingsgraad doorgaans bij hogere zoutgehaltes, terwijl het tegengestelde zich voordeed bij lage zoutconcentraties.
De over korte afstand gevonden verschillen in verzouting bleken vaak samen te hangen met termietenactiviteit. Een uitvoerige beschrijving van dit verschijnsel is gegeven in hoofdstuk 3.
Ook de productie van de diverse graslandtypen is vermoedelijk in hoge mate direct of indirect afhankelijk van mate van verzouting en alkaliteit.
Het ligt in de bedoeling in deel III (in voorbereiding) aandacht aan dit aspect te besteden.
Het laatste hoofdstuk betreft de bodem classificatie; classificatie geschiedde aan de hand van het Amerikaanse systeem (Soil Taxonomy).
Hierbij deden zich diverse moeilijkheden voor, welke een gevolg waren van
- het in onvoldoende mate rekening houden (in Soil Taxonomy) met het voorkomen van prairiegronden in tropische streken;
- de aard van het moedermateriaal, dat in een aantal opzichten duidelijk afwijkt van vulkanische assen elders in de wereld.

Preface

In 1970 I was invited by the director of the Serengeti Research Institute (S.R.I.) to undertake a study on soil/vegetation relationships in the Serengeti National Park in Tanzania. The study was intended to form part of a broad ecological study on the functioning of the so-called Serengeti Ecosystem. The Serengeti Ecosystem is marked by the occurrence of a large variety and number of larger mammals. Of particular importance are the large scale seasonal movements or migrations of large herds of herbivores -namely wildebeest, zebra and Thomson's gazelle- within the boundaries of the Ecosystem. The migrations were thought to be related with the supply of drinking water and food, the latter consisting almost exclusively of green grass. The object of this study was to find out to what extent the botanical composition and production of the vegetation, and namely the grass vegetation, depended on soil conditions. The work was planned to link up with a former study by H.M.H.Braun on the production of the grasslands of the Serengeti Plain.

During the first years (1970, 1971) the research activities included reconnaissance soil and vegetation studies and the setting up of a soil laboratory (for quick analysis) at the S.R.I. In 1972 a reconnaissance soil map of the Serengeti Plain was made. This map, which was also made at the request of Tanzanian authorities, formed the basis for more detailed soil/vegetation studies and generalization of the data obtained. The writing up of the results was started in 1974. The report was intended to consist of three parts:

I. Nature of the study, methods and general information

II. Soils of the Serengeti Plain and their characteristics, including the map

III. Vegetation and soils

This report deals with the Parts I and II; Part III is in preparation.

Contents

Part I: Nature of the study, methods and general information

Fig.1a: Approximate location of the study area within Tanzania.

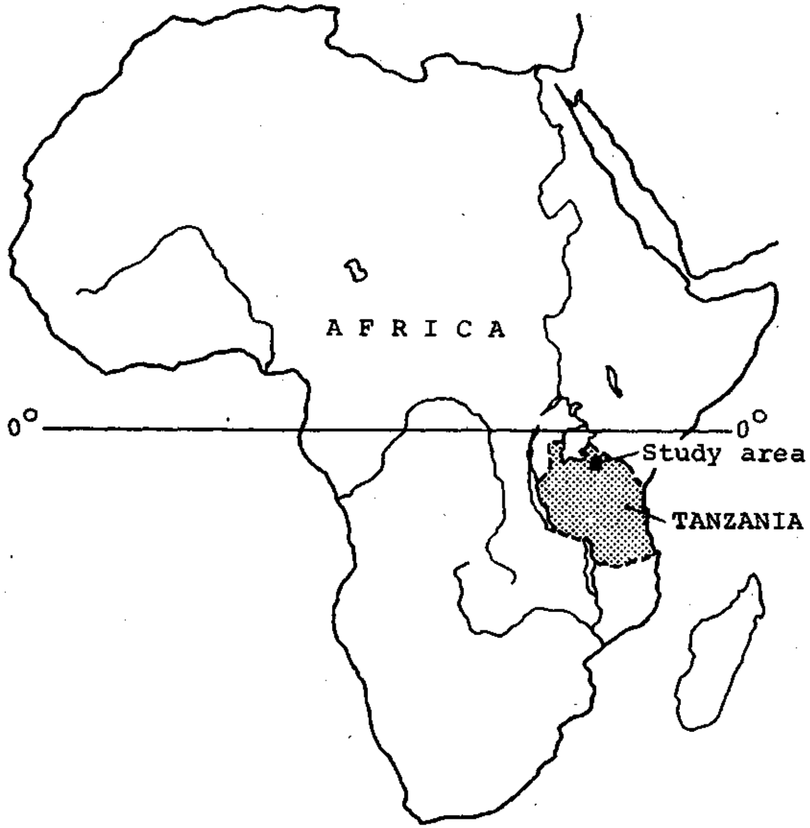
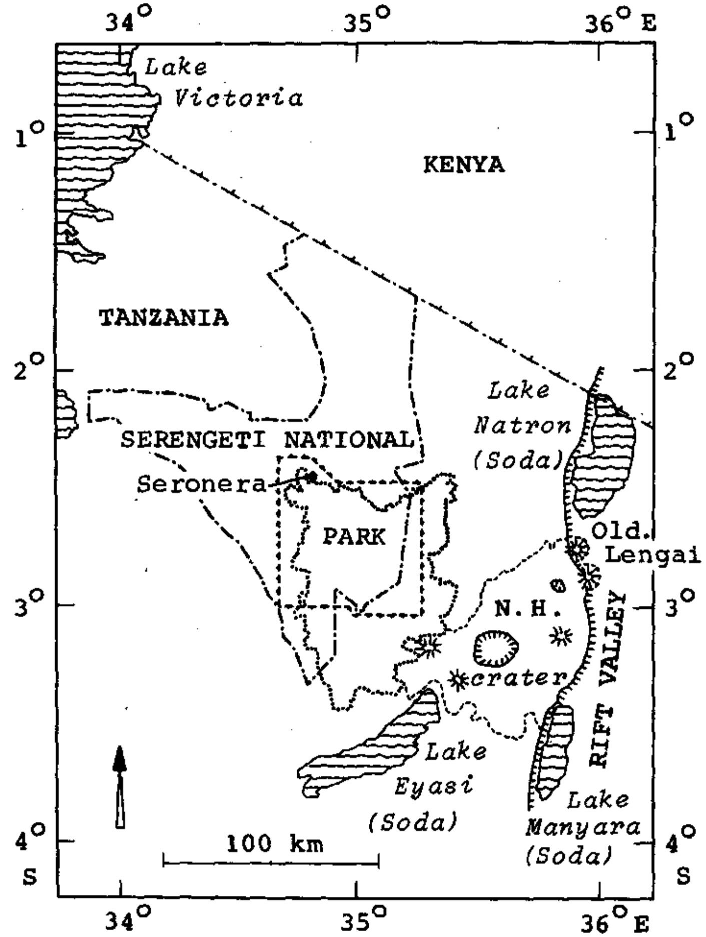


Fig.1b: Location of the Serengeti Plain and the study area.



.... SERENGETI PLAIN

-------- STUDY AREA

N.H. = NGORONGORO HIGHLANDS

1. Introduction

The Serengeti Plain forms a part of the so-called Serengeti Ecosystem, an area of roughly 30 000 square kilometres in north Tanzania just east of Lake Victoria (Fig. 1). The Ecosystem comprises the Serengeti National Park and adjacent areas that form part of game reserves and controlled areas: the Masai Mara Game Reserve north of the Park and parts of the adjacent Loita grassland plain (in Kenya), the Grumeti and Ikorongo controlled areas along the north-western Park boundary, the Maswa Game Reserve to the south-west, and the Ngorongoro Conservation Unit and Loliondo controlled area to the east (Fig. 3a).

Within the area defined as the Serengeti Ecosystem, the Serengeti Plain forms a striking landscape (Land Region 14 according to the classification by Gerresheim, 1974) by its general flat topography and vegetation cover of open grassland.

Elevation ranges from about 2 000 metres in the east to 1 500 metres in the western and north-western parts of the Plain; further westwards, the elevation decreases to 1 135 metres at the shore of Lake Victoria.

Most of the soils of the Serengeti Plain have derived from volcanic ash deposits of Pleistocene age, which have originated from the volcanoes in the Ngorongoro Crater Highlands, that bound the Serengeti Ecosystem to the south-east.

Mean annual rainfall increases from 400 mm in the south-east, near the base of the Crater Highlands, to 800 mm near the north-western edge of the Plain; towards the Mara Region in the north, there is a further increase up to 1 200 mm (Ch. 3: Climate).

Within the open grassland, 3 main grassland zones have been distinguished on species composition and height of the grasses (Watson & Kerfoot, 1964; Braun, 1972, 1973):

Major Vegetation Boundaries

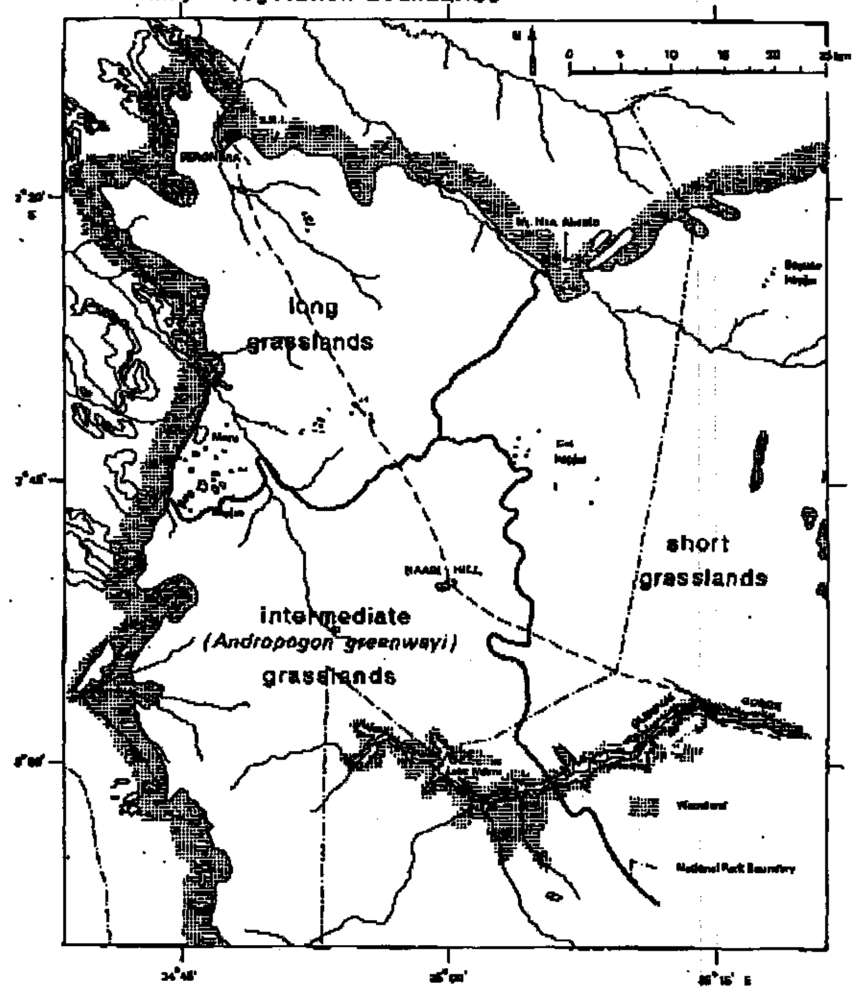


Fig 2a

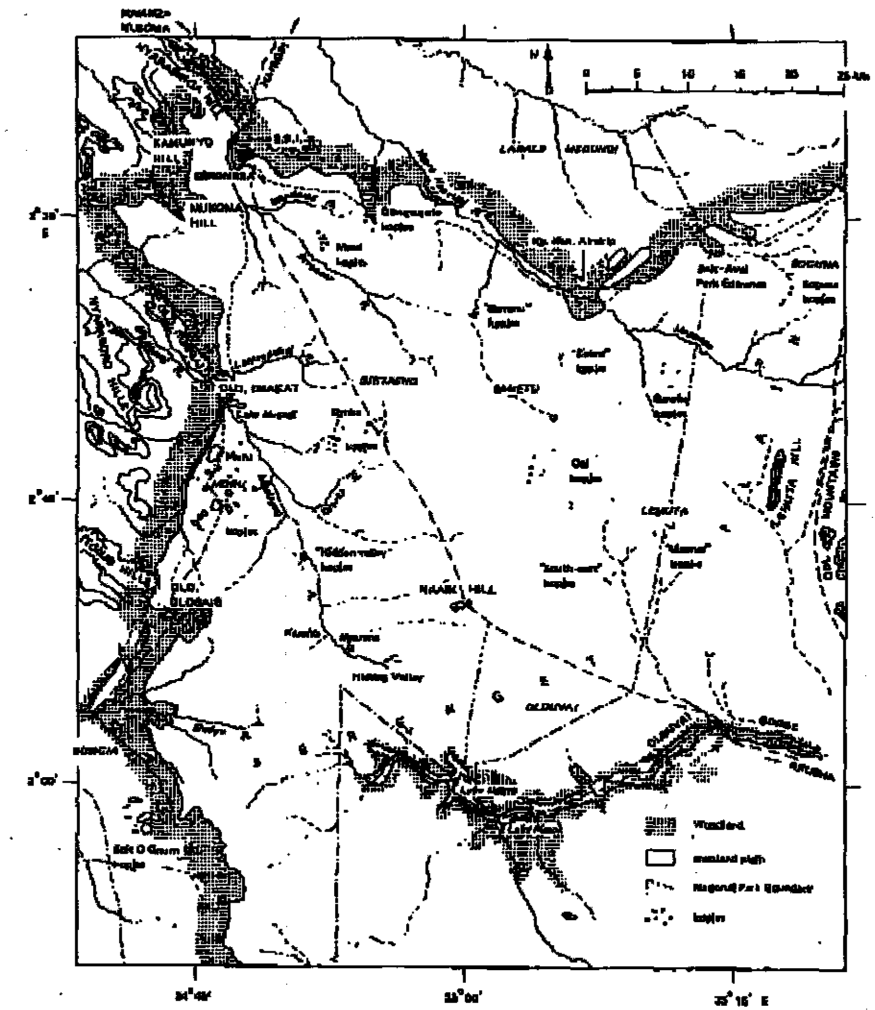


Fig 2b

1. The "Short" grasslands in the east with Sporobolus marginatus A. Rich. and Kyllinga nervosa Steud. (sedge) as characteristic species
2. The Andropogon greenwayi (Napper) or Intermediate grasslands (or medium grasslands in Kreulen, 1975) in the south-west and south with Andropogon greenwayi as the predominant species
3. The "Long" grasslands that are marked by the presence of Themeda triandra Forsk. and Pennisetum mezianum Leeke in the north and north-west.

The distribution of the 3 main zones is shown in Fig. 2a. The other parts of the Serengeti Ecosystem are covered by savannah (usually called woodland) vegetation; trees mostly belong to the genus Acacia. In places with low tree densities the term wooded grassland would be more appropriate; the grasses are tall and heights of over 1 metre occur. In the woodlands adjoining the Serengeti Plain, the grassland composition strongly resembles that of the Long grasslands; further north and westwards, the differences in botanical composition between the grasses of the woodlands and the Long grasslands of the Serengeti Plain are more pronounced.

In the western part of the Serengeti Park - often indicated by the name Corridor - there are several isolated very flat grassland Plains: Ndabaka and Ruwana Plains.

Recent descriptions of various parts of the landscape have been given by Grzimek & Grzimek (1959), Anderson & Talbot (1965), Dirschl & Herlocker (1972) and Kruuk (1972), while Gerresheim (1974) has started a landscape classification system for the entire Ecosystem.

The Serengeti Park and its surroundings are famous for the large variety of species and numbers of large mammals. What makes the Serengeti really unique are the large herds of migratory herbivores of which the gnu or wildebeest (Connochaetes taurinus albojubatus Thomas), the Thomson's gazelle (Gazella thomsoni Günther) and the zebra (Equus burchelli Gray) are the most numerous species.

The migratory herds spend the rainy season, which lasts from November till April (May), on the treeless grassland of the Serengeti Plain. At the beginning of the dry season the herds move towards the western part of the Serengeti Park ("Corridor") and later into the northern part of the Park and the adjacent Masai Mara Game Reserve, where water and fresh grass remain available almost throughout the dry season; at the onset of the rainy season the herds return to the Serengeti Plain.

The migratory movements, described above, have been studied by Grzimek & Grzimek (1959), Watson (1967), Bell (1971), Pennycuick (1975) and Kreulen (in prep.); the boundaries of the Serengeti Ecosystem are, in fact, defined by these migratory movements (Watson, 1967; Pennycuick, 1975).

Various investigators have connected the migration movements with habitat selection; this is quite obvious for the migration in the dry season towards the northern parts of the Ecosystem, that still produce green grass at that time, whereas the grassland vegetation elsewhere in the Ecosystem has withered through prolonged drought. At the onset of the rainy season, the migratory herds of wildebeests head rapidly south and south-eastwards for the Serengeti Plain and, in particular, towards the Andropogon greenwayi (or Intermediate) grasslands in the centre and the Short grasslands in the east, as soon as these areas have produced green grass and provide standing water in pools and waterholes for drinking. Round about the same time, the wildebeests have most of their calves: 80% of the calves are born in January or February within a period of three weeks (Anderson & Talbot, 1965; Watson, 1969). Movements of the animals towards the latter areas, irrespective of the food and drinking water situation in the Long grasslands and in areas outside the Serengeti Plain, indicates a certain preference in the utilization of the Short grasslands and parts of the Andropogon grasslands (Grzimek & Grzimek, 1960; Watson & Kerfoot, 1964; Pennycuick, 1975).

Anderson & Talbot (1965) considered factors like growth stage and palatibility (when drinking water is available) and soil conditions - namely the stickiness of the soil material in connexion with passage - to be related with the preference for these areas; they also concluded from their results that a nutrient factor was unlikely to cause the seasonal preference for the Short grasslands, because nutrients would be more available in the Long grassland soils.

Results on primary production of the various grassland types of the Serengeti Plain obtained by Braun (1973), however, indicated that the Short grasslands produce grass of better quality as judged by content of crude protein, during the relatively short time that these grasslands are green. Preliminary results by Kreulen (1975) on protein, energy, digestibility, Na, Ca, Mg, P, Co, Cu, Mo, Zn and F contents from grass and drinking water, revealed that Ca content and Ca:P ratios might be involved in the selective use of the Short grasslands as well as parts of the Andropogon grasslands; Kreulen (1975) found that Ca contents in water and grass and Ca:P ratios of the diets were more favourable in the Andropogon and Short grasslands; this could be associated with the wildebeests larger requirement for Calcium in the diet during lactation (Kreulen, 1975).

The nutrient factor as a possible key for the migratory movements and preferential utilization of the Short grasslands - possibly in combination with important floristic differences that occur between the main grassland zones of the Serengeti Plain - will be dealt with more extensively by Kreulen (in prep.).

Besides the preferential utilization of the Short grasslands and central parts of the Andropogon grasslands during the wet season there has been a sharp increase in the sizes of the migratory populations - in particular of that of the wildebeests - since 1960, at which time a large part of the ecosystem became a National Park. The number of wildebeests increased from roughly 200 000 in the early 1960s to 735 000 in May 1971 (Norton-Griffiths, 1973); in June 1972 the number had increased to 840 000 animals (Sinclair, 1973) and in 1975 the population seems to have reached the number of 1 000 000. The zebra and Thomson's gazelle also showed a considerable increase in population during this period, but not to the same extent. The population sizes of the above herbivores are largely determined by the amount of available food and predation seems to play a minor role only (Kruuk, 1972). Investigations on primary production and standing crop in the Serengeti Plain have been and are being carried out by several workers: Braun (1973), who worked from 1966 till 1970, Sinclair (1973) from 1970 till 1973 and McNaughton since 1974.

Braun (1973) found higher grass production with increasing rainfall. The increases in production were non-linear and were found to follow different trends for the three main grassland zones when compared for different years. Differences in species composition and grass structure between the main grassland zones as well as between patterns distinguished within the main zones, possibly in combination with soil factors, were considered to be responsible for this.

Braun's investigations and results have directly led to the study on soils and grassland vegetation in the Serengeti Plain undertaken by the author (1970-1973). This study was on the following questions:

1. What soil types are found in the Serengeti Plain? What is their regional distribution? What are the most important differences in physical and chemical properties and which factors cause of have caused these differences?
2. To what extent are the floristic composition and grass heights of the main grassland zones determined by differences in soil conditions?
3. In what way and to what extent are the qualitative and quantitative production of various grassland types influenced by soil conditions?

Anderson & Talbot (1965) distinguished a number of broad soil/grassland associations and established the occurrence of a sequence of soils in east-west direction across the Serengeti Plain showing an increase of profile development and clay contents, which they ascribed to be influenced by the following:

- the nature of parent material - Anderson & Talbot mention the ash deposits becoming finer textured from the east towardsthe west (textural gradient correlated with the distance from the sources of the ash deposits) while the soils beneath the Long grasslands would have had very little, if any, ash addition, and would therefore not fit in the sequence
- a climatic gradient (in particular rainfall, increasing from the south-east towards the north-west)
- a time gradient.

From data on morphology and chemical properties of the soils, Anderson & Talbot concluded that distribution of the grass species - namely of the Short, Intermediate and Long grasslands, also called "broad grassland associations" - the growth stage and vigour of the grass species are largely determined by erodibility of the soils and soil depth, soil texture and salt concentrations, all of which affect moisture availability; variations in the vegetation pattern within a broad soil/vegetation can be explained either by burning and grazing patterns or more locally on the basis of the catena. Grazing effects were considered especially important for species composition and basal cover of the grassland of the eastern plain (Short grasslands) and the south-western plain (*Andropogon greenwayi* grasslands). Although the results of Anderson & Talbot give only a qualitative picture of the relationships between soil conditions and grassland types, they formed a useful starting point for further research. From a combination of results given by Anderson & Talbot (1965) and by Braun (1973) and data collected during the first half year by the author, the following hypothesis was formulated:

The distribution and the production of the various grassland patterns, subpatterns and grass species within the Serengeti Plain are considered to depend - as far as soil conditions are concerned - on various combinations of the following factors:

1. Salinity:

   selective effect on species distribution by toxic and competitive effects on ion uptake for certain species, osmotic effects on water availability for sensitive grass species.

2. Alkalinity:

   competitive effects on ion uptake of certain species; indirect effect on the availability of water in certain soils by causing dense soil layers that are almost impermeable for roots and precipitation.

3. Water availability :

   most important factor in determining grass production; the availability depends on combinations of:

   - total rainfall and its distribution during the year
   - rainfall intensity
   - permeability of surface layer and lower horizons
   - profile depth to which roots can penetrate, which depends for many profiles on the depth of a petrocalcic horizon, a natric horizon or a salic horizon
   - pF characteristics of the rooted soil horizons, which depend on soil texture, structure and porosity.

The distribution of the various grass species was expected to be especially related to the factors salinity, salt composition and alkalinity, and the production was expected to depend largely on the availability of water, which, in its turn, appeared to be largely determined by rainfall, thickness of the rooted soil layer and water retention.

Investigations have concentrated on the three above factors; for this purpose a small soil laboratory has been set up at the Serengeti Research

Institute at WOTRO expense. Handling soil-samples on the spot had several advantages over having the samples analysed at a commercial laboratory: much lower costs and the immediate availability of data, which saved much time and allowed decisions more quickly on further steps. Details of analysis that have been carried out are described in Chapter 2: Methods.

First investigations were made on soils of former grassland production plots of Braun (1973) that had been laid out in a number of representative grassland types. These activities resulted in a picture of the range of morphological, physical and chemical characteristics of the soils at the selected grass production sites.

At this stage of the study the distinction between various soil types and also their preliminary classification had entirely been tied up with the occurrence of a number of important grassland types of known floristic composition. Hence, the significance of the differences in morphology, and physical and chemical properties that were found between soils of sites investigated could be estimated for a few sites only, namely for those in which the sites formed of formed part of a topographic sequence or catena (Milne, 1935).

In 1971 I started to make a reconnaissance soil map based on geomorphological characteristics (Stage 2); aerial photographs formed an invaluable aid. With the help of this map, the whole area could be assessed from the soil data collected during the study. Generally, soil and vegetation boundaries were found to coincide in many places, especially within catenas. The results, obtained from the investigations that belonged to the Stages 1 end 2, are extensively described in Part II: "Soils of the Serengeti Plain and their characteristics", and have given answer to most of the questions put under point 1 of the objectives of the study mentioned on page 7 .

Part II deals also with the relationships between vegetation patterns of different floristic composition and soil conditions, of which salinity and alkalinity were the most important variables. On several occasions, salinity and alkalinity patterns could be ascribed to biological activity in the soil, namely by termites; their activity proved to have a strong indirect influence on grassland composition. Although it was originally intended to deal with vegetational aspects exclusively in Part III (Vegetation and Soils), certain vegetation patterns and soil conditions appeared so closely linked, that separate discussions would have given an incomplete picture and unsatisfactory explanations of the processes.

Part III summarizes the most important grassland types, their distribution and their relationships with soil properties. Details on floristic composition can be found in Braun (1973) and Kreulen (in prep.).

The mineral contents of the grass species or combinations of species may form a clue for the preferential utilization of the Short grasslands and parts of the Andropogon grasslands by wildebeests and other migrants. Two aspects were to be investigated:

- Are there significant differences in mineral contents between leading species that characterize the 3 main grassland types distinguished?
- Are there significant regional differences in mineral contents within individual species that occur commonly in all main grassland types?

The results will be discussed in a separate publication.

Anderson & Talbot (1965) mentioned the strong influence of the factors climate and geology on the soil formation, while Braun (1973) established relationships between grassland production and rainfall. Special attention to these factors has been paid in Chapters 3 (Climate) and 4 (Geology). Chapter 2 deals with methods, procedures and equipment used during the research activities.

2. Methods

2.1. Fieldwork

I. Soil studies

Soil profiles have been studied from 50 soil pits. Pits have been dug to depths between 120 and 200 cm (150 cm on the average) or down to a lithic contact.

In the first stage of the study, soil pits were dug at sites selected before by Braun (1973) for his grass production experiments; later the sites were selected from a preliminary reconnaissance soil map. The compilation of the soil map was largely based on the interpretation of aerial photographs (Part II).

1. Soil profile descriptions

a. General characteristics: they give information on the site of the soil profile, the physiography, parent material, slope, relief, erosion, drainage condition, moisture contents throughout the profile at the time of investigation, natural vegetation, landuse, root distribution and biological activity and special features, if any.

Terminology and classes have been applied according to the Soil Survey Manual (SSM, 1951).

b. Soil profile characteristics:

- description of the soil horizons (thickness)
- colour of the soil material (Munsell)
- estimation of the soil texture by rubbing and from consistency at various moisture contents;the classes estimated in this way have been corrected with the help of laboratory data.
- descriptions of soil structure: type, class and grade.
- descriptions of the consistency of the soil material (wet, moist and dry)

- descriptions of the porosity.
- descriptions of the root density, concretions, mottling (size, contrast, abundance, colour).
- descriptions of special features like gravel, faecal pellets, dung balls, termite nests, artefacts.

In most cases terminology has been applied according to the Soil Survey Manual.

Porosity classes, however, have been defined somewhat arbitrarily:

- micropores: pores smaller than 0.1 mm diameter, only visible at magnification.
- mesopores: pores between 0,1 and 2 mm diameter.
- large pores: pores over 2 mm diameter.

The micropores are constituted by the intra aggregate pores; the mesopores may be both of the intra-aggregate and inter-aggregate type of pores, whilst the large pores refer exclusively to the inter-aggregate pores or cracks.

In soils in the eastern part of the study area the porous space formed by micro and smaller mesopores was often very high, comparable with the porosity of a loess soil; the porosity in these soils has usually been characterized by the term "sponge porosity". Besides the pores that own their existence to physico-chemical processes, there are "biopores", that have originated by biological activity, e.g. root channels and insect holes. According to the diameter, meso-biopores (0.1-2 mm) and large (over 2 mm) biopores have been distinguished. Often mesopores and large pores were probably biopores; identification as such was often difficult.

Some remarks should also be made about the terms <u>size</u> and <u>abundance</u> with respect to roots:

Root "sizes" refer to the root diameters:

diameter smaller than 0,5 mm	: fine roots	(mainly grasses)
diameter between 0,5 and 2,0 mm	: medium roots	(mainly grasses)
diameter over 2,0 mm	: large roots	(mainly herbs, etc.)

Estimation of the abundance of roots according to the limits given in the SSM (1951) as given for mottles led easily to the underestimation of the total mass of roots; for roots the limits have therefore been changed as follows:

few roots:	much less than 1%
common roots:	up to 2%
many roots:	over 2%
abundant roots:	for some surface soils (top 18 cm)

It is recognized that the above classification of pores and roots is very subjective; Soil Taxonomy (1975) gives a more detailed classification for soil pores according to Johnson et al. (1960). The amounts of concretions and other coarse fragments have been estimated according to the limits given for the abundance of mottles as given in the SSM (1951).

2. Soil Sampling

a. Sampling by spade from soil pits.

Samples have been collected from the walls used for the profile description. This had the great advantage that the samples could be collected per soil horizon or part of it.

11 So-called standard profiles - i.e. the ones chosen as most representative for important soil units - have been sampled by spade.

b. Sampling by auger (Edelman-type).

Samples have been collected per 10 cm layer (or 20 cm) as mixed samples from 2, 3 or 4 spots taken at equal depths.

The 2 to 4 sampling spots were located in a small area of 1 to 2 m^2 that supported a homogeneous vegetation as far as coverage and

species composition were concerned.
The method of 2-4 point sampling has been applied in many places, firstly because it was a fast method, and secondly because it did provide a sufficient quantity of soil material - i.e. sufficient to have all analysis procedures required carried out - whereas a single point sample did not.
The auger method has been checked against sampling from soil pits with respect to horizon differentiation and appeared to give especially good results for soils of the central and eastern parts of the study area.
Within distances of a few meters only there were variations in patterns of distribution of free salts, especially in the Short and Intermediate grasslands; the mixing of samples from one level had therefore a levelling effect on the chemical status of the soil layer investigated. To estimate the order of magnitude of the local differences, single point sampling has been carried out at several sites. The differences appeared to be small as long as the samples had been taken from spots covered by a grass vegetation of a similar botanical composition.
Soil sampling by auger, however, was hardly or not feasible in layers that were rich in hard lime concretions and that were often found within a depth a 1 metre, while a petrocalcic horizon, which occurs abundantly in the soils of the Short grasslands within a depth of 50-100 cm, appeared to be absolutely impermeable, thus forming the ultimate depth for sampling.

3. Ring sampling

Stainless steel rings with contents of 100 cm^3 (5.0 x 5.1 cm) have been used to take undisturbed soil cores; these samples served for the determination of the moisture contents at low moisture stresses

(pF 1.0 and 2.0) and for the determination of the bulk densities. The samples have been collected vertically from pre-moistened soils in a soil pit.
Undisturbed samples for pF determinations at higher moisture stresses were obtained from undisturbed clods from soil samples taken by spade. (see also Laboratory work).

4. Infiltration experiments

Infiltration experiments have been carried out with single cylinders of 7,5 cm x 6,4 cm cut from LandRover shock absorbers. The rings were pushed 3-4 cm into the soil layer investigated; during the first experiments by hitting the rings into the soil, later on the rings were pushed gradually into the soil by using a jack and the weight of a LandRover. The latter method was preferred since the hitting of the rings caused many fine cracks in the soil layer to be investigated, which resulted in too high infiltration rates. Surface infiltration was mostly done in bare spots that formed very shallow depressions between grass clumps. In case experiments were made in cracked surface soils or cracked subsoil layers - e.g. in the more clayey soils of the western half of the study area - the rings have been put in places without or with a minimum number of wide cracks; in soil layers with a regular pattern of cracks, however, the rings have been pushed into the soil randomly. The infiltration experiment was carried out by pouring a measured quantity of water (ml) from a container into the ring; the soil within the ring had been covered before by a disc of filter paper to protect the surface layer against slaking.
The infiltration rate (mm/h) was calculated from the time (measured with a stopwatch) in which the total amount of water used had penetrated into the soil. Immediately after the soil inside the rings

had become dry, the experiment was repeated - using the same number of mm water - till a more or less constant infiltration rate was obtained.

In most experiments a head of 12,43 mm ($\approx$ 0,5 inch) was used by pouring out 40 ml water. Depending on the permeability of the soils investigated also other amounts have been used in order to obtain as many data as possible: 3,218 ml corresponded with a head of 1 mm.

II. Vegetation studies

1. Vegetation descriptions.

Vegetation descriptions were made at all sites from which soil samples had been taken. The description only referred to the vegetation that surrounded the soil pits - namely on the side of the described wall - and to the small areas sampled by auger.

Initially the abundance of the individual species was estimated from their basal cover (tufts and stolons) using a tenfold scale according to Braun (1972):

+	species	contributing	less than 1%	to	the	basal	cover
1	"	"	from 1 to 5%	"	"	"	"
2	"	"	from 5 to 10%	"	"	"	"
3	"	"	from 10 to 20%	"	"	"	"
4	"	"	from 20 to 30%	"	"	"	"
5	"	"	from 30 to 40%	"	"	"	"
6	"	"	from 40 to 50%	"	"	"	"
7	"	"	from 50 to 60%	"	"	"	"
8	"	"	from 60 to 70%	"	"	"	"
9	"	"	more than 70%	"	"	"	"

Estimations from the basal cover had been chosen because this greatness was thought to be the least sensitive to seasonal variations, e.g. due to selective grazing, trampling, burning or erosion. The actual soil coverage of the species could be calculated later on on the basis of estimations of the so-called total soil cover of the vegetation. The latter appeared feasible because overlapping of the species did seldom occur. Problems did only arise in case the vegetation was rich in herbs, for instance on the flanks of ridges and in the broad valleys in the Andropogon greenwayi grassland, where certain herbs formed a dominant aspect of the vegetation. On such occasions a special note on the occurrence of the various herbs was made.

2. Grass sampling

Grass samples for analysis of the mineral contents and crude protein have been mostly collected from leaves of young shoots (equal stage of growth); for lack of young materials older leaves have been taken occasionally.
The samples were dried at 60°C for 18-24 hours and finely ground with a Culatti Cu 10 grinding mill preceeding the chemical analysis. Most of the samples have been collected in connection with soil studies.

A summary of all fieldwork activities both on soils and vegetation is found in Table 1 at the end of this chapter.

2.2. Laboratory work

1. Handling of soil samples

Soil samples have been put in open aluminium trays and dried in a drying oven with fan convection at 30 °C for at least 24 hours (air-dry samples). After the drying 0,5-1 kg of soil material was lightly crushed by a mortar and sieved through a 1.7 mm sieve (round holes), by which the greater part of medium and fine roots and all hard concretions and gravel of over 1.7 mm diameter were removed from the sample. Samples that were not for immediate use were stored in polyethylene bags. The remaining part of the air dry soil was also stored and kept as a reserve from which natural aggregates could be collected for pF tests at high tensions and other purposes.

2. Chemical determinations on samples

a. Preparation of soil extract.

Chosen was the saturation extract according to the U.S.D.A. Handbook 60 (1954). Appr. 500 gram of sieved soil material and deionized water (Zerolit Mark 8H) were used for the preparation of a saturated paste. The saturated paste was kept overnight to equilibrate; in case the puddle appeared to be too dry some more water was added, while some soil material was added in case the opposite was found. From the paste a subsample was taken for the determination of the saturation percentage (SP), i.e. the percentage of water by weight at saturation. The soil pastes itself were extracted in series of ten under vacuum by which the saturation extract were obtained. Immediately before extraction the pH of the saturated paste (pH_p) was measured.

b. Measuring of the pH.

Measurements in 0.01 pH units were made with a Pye-Unicam Model 290 (readability 0.01 pH unit) using glass electrode (Philips GA 420) and calomel electrode (Philips R 11) in:

- saturated paste (pH_p)
- saturation extract (pH_e).

Whereas the pH of the soil paste could be read almost immediately, the pH of the extract tended to shift during the measurements to a greater or lesser extent depending on the soil type investigated: slight shifts in extracts from samples of the Short grassland soils (which had high pH values) and considerable shifts (toward higher pH values) in extracts from Long grassland soils, which had lower pH_p values than those of the Short grasslands. A combination of factors may be responsible for this phenomenon; the explanation of it, however, lays beyond the scope of the study.

c. Conductivity of the saturation extract: EC_e (mmho[1]/cm at 25 °C).

Measurements in the saturation extracts were made with a Cenco Conductivity meter using a Philips conductivity cell Type 9513. After the temperature of the extract was set on the instrument the conductivity was read in micromho/cm at 25 °C. Dividing by 1000 gave values in millimhos.

With the EC_e a fairly accurate estimation could be made of the amounts of soluble salts in the extract, except for those, rich in carbonates.

d. Determinations of cations in milliequivalents/litre of the saturation extract.

- Na^+ and K^+: determinations were made flame photometrically (EEL Model 100, butane/air mixture). The extracts have been diluted such that K concentrations could be measured in the linear range (0-3 mg/litre); for Na determinations a calibration curve was made (0-4 mg/litre).
- Ca^{2+} and Mg^{2+}: determinations were made with EDTA (ethylenediaminetetraacetate) according to the procedures described in USDA Handbook 60 (1954).

In all extracts investigated Ca + Mg was determined while separate test for Ca were done for a limited number of extracts. Subtracting the Ca concentrations from the Ca + Mg data gave the Mg

1) = mS

concentrations.

The Ca + Mg determinations on samples taken from non-saline parts of Short grassland profiles appeared to be interfered: near the end point of the titration there was a very gradual change of colour in stead of an abrupt one, while there was a "colouring back" of samples that had been standing for some time after the end point had apparently been reached. This interference was likely to be due to the presence of light yellowish-brown very fine soil particles including lime and possibly also amorphous material with high exchange capacity in the extract, that had passed through the filter during the extraction of the saturated paste giving the extract a turbid appearance.

The soil material was- as it appeared from determinations of exchangeable bases - rich in Ca (lime and exchangeable Ca) which may have been titrated in addition to soluble Ca and Mg, thus resulting into too high Ca+Mg concentrations in the extract. This would account for both the slow colour change and the too high sums of cations in comparison with that of the anions in the extract. The interference could be limited by pipetting a subsample (to be analysed for Ca+Mg) from the upper part of the extract after it had been standing for some time and most of the soil material had settled on the bottom of the container.

e. <u>Determination of the anion concentrations (meq/litre of the saturation extract).</u>

- <u>Carbonate and bicarbonate.</u>

Determinations have been carried out by using a pH meter (Pye-Unicam, Model 290) glass and calomel electrode, according to the method described by Van Beek & Kamphorst (1973):

A diluted subsample is titrated with 0.01 N H_2SO_4: the titration is monitored on the pH meter; electrodes permanently immersed in whirling sample (magnetic stirrer).

The relative amounts of CO_3^{2-}, HCO_3^- and H_2CO_3 in the soil extracts have been described by Novozamsky & Beek: Carbonate equilibria, in: Bolt and Bruggenwert (1976). A short summary follows below:

pH	4.5	8.5	12.5
CO_3^{2-}	-	(+)	+
HCO_3^-	-	+	-
H_2CO_3	+	(+)	-

- absent; (+) small amounts present; + constituting nearly 100%.

For samples that contained carbonates (pH>8.5) the titration was stopped when the point pH 8.5 was reached; the number of ml H_2SO_4 used was read from the buret: y. After that the titration was continued till the point of pH 4.5; this gave the second buret reading: z.

USDA Handbook 60 (1954) gives the formulas for calculating the carbonate and bicarbonate concentrations of the original sample:

$$\text{meq/litre } CO_3^{2-} = \frac{2\ y \times \text{normality of } H_2SO_4 \times 1000}{\text{ml in aliquot}}$$

$$\text{meq/litre } HCO_3^{-} = \frac{(z - 2y) \times \text{normality of } H_2SO_4 \times 1000}{\text{ml in aliquot}}$$

The results obtained in this way did not reflect the actual ratios between the CO_3^{2-}, HCO_3^- and H_2CO_3 concentrations in the saturation extract since the acid water (pH 4.5) used to dilute (about 10 x) the sample from the saturation extract lowered the pH considerably. For many samples only the sum of carbonate and bicarbonate has therefore been determined; since the pH of the original saturation extracts are known, the actual CO_3^{2-} and HCO_3^- concentrations in the extracts can be calculated afterwards (if desired).

- Chloride

Potentiometric determination as described by Van Beek & Kamphorst (1973) using a Pye-Unicam 290 pH meter in combination with a Ag electrode (Radiometer Type P 4011) and a Hg/Hg_2SO_4 reference electrode (Radiometer Type K 601).
Diluted samples, pipeted from the saturation extracts and acidified to a pH of 3.0 by adding some nitric acid, were titrated to a fixed equilibrium potential (appr. - 90 mV) which had been established before by titrating a standard 0.01 N KCl sample against an approximately 0.01 N $AgNO_3$ solution: from this titration also the exact normality of the $AgNO_3$ was found.

$$\begin{array}{l}\text{meq } Cl^-/\text{litre} \\ \text{(saturation extract)}\end{array} = \frac{\text{ml } AgNO_3 \text{ used x normality } AgNO_3 \text{ sol.x } 1000}{\text{ml in aliquot}}$$

- Sulphate

Two methods have been used.

1. By photoelectric colorimeter (Vitatron UC 200 S) using a 439 nm filter.
   Sulphate was precipitated by $BaCl_2$ in a Tween 80 soap solution; the Tween 80 kept the precipitate in suspension. Transmission was measured at 439 nm and checked against a calibration curve.
   This method, which had been derived from Methods of plant analysis applied by the Dept. of Soils and Fertilizers of the Agricultural University of Wageningen, has been abandoned, because of its poor reproducibility.

2. By titration with barium perchlorate in isopropanol with Thorin as an indicator and barium sulphate as a catalyst; standards and samples were acidified to pH 3.0 with perchloric acid. This method has been derived from Van Beek & Kamphorst (1973); however, isopropanol was used instead of the ethyl alcohol prescribed.The sulphate determination was a much time consuming and costly one. For a considerable number of samples sulphate determinations have been omitted except for some checks; the sulphate concentration in the saturation extract (meq/litre) could be estimated by subtracting the sum of carbonate, bicarbonate, chloride and nitrate from the sum of cations.

- Nitrate

Initially only qualitative tests for nitrate after Feigl (1954) have been made using diphenyl amine in concentrated sulphuric acid as a reagent.

Later on, when free nitrates were found to be quite often an important component of the salts, this method was modified to a semiquantitative one by comparing the intensity of the blue colouring of the extracts upon addition of the reagent with a number of standards containing increasing amounts of nitrate:

o,5   1,0   2,0   3,0   4,0   meq/litre

Estimating concentrations of over 4,0 meq/litre became unreliable because the colours became too dark. Estimations of 0,25 meq/litre below the limit of 4,0 meq/litre could be made with acceptable accuracy.

f. Cation exchange capacity (CEC) and exchangeable bases.

Determinations of the CEC and exchangeable bases were made by the percolation method. For both determinations mixtures of 4 gms of soil material (< 1.7 mm) and 40 gms of purified quartz sand were put into percolation tubes I (CEC) and II (exch. bases).

I: CEC: exchangeable calcium and magnesium

a. percolation by 100 ml 1N sodium acetate; in the percolate exchangeable Ca and Mg were determined titrimetrically (with EDTA in sodium acetate environment) followed by

b. washing with 70% isopropanol, several times 10 ml, followed by 1 x 100 ml followed by

c. percolation with 100 ml 1N ammonium acetate; from this percolate the CEC was found by the flame photometric determination of Na (displaced by ammonium).

II: Exchangeable bases (Na, K)

percolation with 100 ml 1N ammonium acetate; in the percolate exchangeable Na and K were determined flamephotometrically. N.B. Ca and Mg could not be determined in this percolate because the titration was interfered by NH_4, while also a considerable amount of lime became dissolved which was also titrated; the latter process was less relevant in the sodium acetate percolate (I a) because of the higher pH (pH 7-8).

In contrast with what was expected, appreciable amounts of K were found in some of the NH_4 percolates (I c). This indicated that the displacement of exchangeable K by Na in stage (a) had been incomplete or that the K had been preferentially exchanged by the ammonium ions in stage (c).

The latter assumption was supported by the fact that in certain samples the sum of exchangeable bases exceeded the CEC, which might be due to too high amounts of exchangeable K (Obtained from the ammonium percolate II).

Because of these uncertainties some additional CEC experiments were made according to a modified method after Bascomb (1964): percolation of the soil with 1N barium acetate followed by washing with 70% isopropanol till no barium could be detected any longer in the percolating isopropanol using sulphate as a reagent; after that the soil columns were leached by exactly 100 or 200 ml of appr. 0.05 N $MgSO_4$ (normality exactly known) - by which the adsorbed barium was compulsorily exchanged by magnesium (precipitation of Ba as barium sulphate) - followed by repeated washing with deionized water to remove soluble $MgSO_4$ that had remained in the column.

In the percolate a sulphate determination was made from which the number of milliequivalents Ba precipitated by $MgSO_4$ - being equivalent to the CEC - could be calculated by subtracting the number of milliequivalents sulphate left in the percolate from that in the original 100 or 200 ml of the magnesium sulphate solution.

Tests for the presence of gypsum in the soils investigated - which could have interfered seriously - had a negative result.

g. Lime.

Lime determinations have been done on the fine earth fraction (< 1.7 mm) only. Soils or soil layers rich in lime concretions may therefore have higher lime contents than those found in their fine earth fraction.

The lime contents were determined by gravimetric loss of carbon dioxide according to the method described in Handbook 60:

weight of CO_2 lost = (initial wt. of flask + hydrochloric acid + soil) - (final wt. of flask + acid + soil).

$$CaCO_3 \text{ equivalent } (\%) = \frac{\text{weight of } CO_2 \text{ lost}}{\text{wt. of soil sample}} \times 227.4$$

Weight measurements were made in 4 decimals (0.1 mg) using a Mettler H-10 balans. The final weight of the flask + acid soil was reached when the loss of weight had become equal to the loss of weight of a blank (flask + acid) due to evaporation of water only; the final weight was corrected for the loss of weight by evaporation.

3. Physical determinations

a. Moisture contents

- moisture percentage by weight.

  Samples were dried at 100 °C for at least 16 hours continuously. Weight measurements of samples of over 10 gms with a Mettler P 1000 balance.

  $$\% \ H_2O \text{ (weight)} = \frac{\text{weight moist soil - weight dry soil x 100}}{\text{weight dry soil}}$$

- moisture percentage by volume:

  % H_2O (vol) = % H_2O (weight) x bulk density (in g/cm^3) (density of the water was assumed to be 1,00)

b. Bulk density

Ringsamples of exactly 100 cm^3 (stainless steel cylinders), moistened throughout, or in the field before sampling or during pF experiments, taken in vertical position from undisturbed soil layers (profile pits) were dried at 105 °C for at least 2 consecutive periods of 16 hours continuously drying.

$$\frac{\text{weight of dry sample}}{100} = \text{bulk density (g/cm}^3\text{).}$$

c. Moisture contents at various moisture tensions: pF determinations

- pF 0, pF 1 and pF 2 determinations.

  These determinations have been carried out with undisturbed ring samples of 100 cm^3. From these determinations moisture

contents were obtained that were in equilibrium with moisture tensions (matric suction) of resp. 1, 10 and 100 cm. The under pressure (suction) on the samples was realized by placing the saturated or nearly saturated samples on top of a sand column ("sand bath") at which surface the required underpressure had been created by the weight of a column of capillary water rising from a watertable of which the depth below the surface of the sandcolumn could be adjusted by lowering or rising a water container that was connected by rubber tubing with a drain system in the lower part of the sand column. The capillary rise of water depends on the diameter of the pores; in homogeneous soils the diameter is determined by the average particle size.
For the pF 0 (only determined occasionnaly because of the greater risk of destruction of the sample) and pF 1, determinations were carried out on a sandbath containing fine and medium sand (0,1-0,5 mm); the sandbath was constructed from a 200 litre oil drum and had a capacity of 30-35 samples at a time. Starting from a saturated sample the watertable was gradually lowered to 1 (pF 0) and to 10 cm below the centre of the ring sample which lay 2,5 cm above the sand surface; equilibrium was reached within one day.
After measuring the weights, the ring samples were saturated again and placed on a similar sand bath, this time consisting of silt (20-75 microns) with a water table kept at 100 cm below the centre of the sample (pF 2.0). Equilibrium was reached after 2 days for most soils. After that the samples were dried at 105 ^{o}C to find the dry weight per 100 cm^{3} (bulk density).
Clayey samples from the western part of the study area (Andropogon greenwayi and Long grasslands) appeared to shrink

to a greater or lesser extent upon drying (after having swollen at the beginning of the experiment). From the shrinking of the sample the coëfficient of linear extensibility (COLE) was estimated[1]).

For this purpose the volume of shrinkage was estimated from the volume (cm^3) of loosely packed medium sand necessary to fill the open space between the steel cylinder and the dried soil core (upper and lower side covered by aluminium lids); the sand volume was found by pouring the sand into a measuring cylinder. Assuming that the shrinkage of the sample was proportionally equal for both the vertical and radial direction, the linear shrinkage could be calculated from the formula:

$$V = 3{,}14 \left\{0{,}5(R-x)\right\}^2 (R-x)$$

in which:

V = volume of shrink (cm^3)

R = diameter=height of moist ringsample (100 cm^3)=5,03 cm

x = shrink (cm)

- pF 4,2 and pF 5,6 determinations

Because no pressure membrane apparatus was available, the estimations of the moisture contents at high tensions have been obtained by the vapour pressure method with controlled relative humidity, as described by Stakman (1963).

Moisture contents at pF 4,2 were obtained by allowing the

1) According to Soil Taxonomy (1975) COLE has been defined as

$$\frac{R_{moist} - R_{dry}}{R_{dry}}$$

R_{moist} = diameter of sample at pF 2.0

R_{dry} = diameter of sample after drying 24 hours at 105 °C moistened soils to equilibrate with an atmosphere with a relative humidity of 98,8%; the latter is effected in a vacuum desiccator with a saturated solution of ammonium oxalate. For determinations at pF 5,6 a saturated solution of sodium chloride creating an atmosphere with a relative humidity of 75,8% was used.

One of the conditions during the experiments was the need for a constant humidity; temperature fluctuation should be kept to a minimum because of its effect on the solubility of the salts used and consequently on the relative humidity.

The determinations were carried out as follows: crucibles of known weight, containing 2-3 grams of very fine, moistened natural soil aggregates were placed into a vacuum desiccator with a saturated ammonium oxalate solution after which most of the air was evacuated. The desiccator was placed in an air-conditioned room in which the temperature was kept at 20 °C during most of the day. After one week the weights of the crucibles plus the samples were measured with a Mettler H-10 balance to four decimals (0,1 milligrams) every one day until weights had become constant. During the measurements evaporation (humidity of the air was usually less than 50%) was a disturbing factor; the loss of weight due to evaporation was estimated for each sample by weighing the whole serie of samples twice. Constant weights were obtained after 2-4 weeks; heavy clayey soils tended to reach the equilibrium quicker than silty soils. After that the samples were placed in the desiccator for pF 5,6 determinations; constant weights were obtained within 7-10 days. Finally the samples were dried at 105 °C for at least 16 hours after which their dry weights were determined.

The moisture percentages by weight have been converted into volumetric percentages by multiplying them by the bulk density values found for the corresponding soil layers.

d. Soil texture

Mechanical analysis was made on 62 samples of 11 selected profiles (standard profiles). 56 Samples have been investigated at the laboratory for soil and crop testing at Oosterbeek (Netherlands).

The following textural classes have been distinguished:

$< 2\,\mu m$	(clay)
2-16 μm; 16-50 μm (16-50 μm estimated)	(silt)
50-105, 105-210, 210-300, $> 300\,\mu m$	(sand)

Samples have been pretreated with 1N hydrochloric acid and perhydrol to remove lime and organic matter.

All samples investigated contained amorphous material (volcanic origin of the soils!) which became dissolved, to a limited extent, during the pre-treatment with acid; certain samples (e.g. from the BARSEK profile) contained also zeolites which became totally dissolved by the HCl. In order to estimate the effect of the destruction of the amorphous material (and zeolites) on the particle size distribution between the fractions distinguished, soil textures of 6 samples of different profiles have been determined according to a different method, by which the lime became dissolved but the amorphous material and zeolites stayed intact. This was achieved by pre-treatment with Na-EDTA in a buffered solution of a pH of 6,0 (by using Na-acetate) followed by a treatment with perhydrol to remove the organic matter.

Of one profile (BARSEK) all samples have been treated in this way.

e. Total elemental analysis

X-Ray fluorescence (Philips PW 1540, samples pretreated with Philips PH 1006/13) was applied to:

- total soil, including soluble salts (56 samples)

- clay (56 samples); for this purpose a subsample of a Na-saturated clay suspension was taken from a fully dispersed soil suspension of which lime and organic matter had been removed; after that, the sodium clays were converted into barium clays.

f. Mineralogical analysis

a. Analysis of the clay fraction by X-ray diffraction, using a Philips PW 1012/10 apparatus.
Diffractometer traces of 26 Mg-saturated clay samples, 9 Mg-clays treated with glycerol and 4 K-saturated clays have been made.

b. Analysis of the sandfraction.
For a qualitative picture, the light and heavy fractions of each sample have been separated on the basis of specific gravity using bromoform as a medium for separation.

4. Plant analysis

36 Grass samples have been analysed at the laboratory for soil and crop testing at Oosterbeek for Na, K, Ca, Mg, P and Crude Protein (c.p.). 35 samples at the Dept. of Soils and Fertilizers of the Agricultural University of Wageningen, for Na, K, Ca, Mg, P, Cl, NO_3, SO_4 and crude protein.
Na, K, Ca and Mg have been determined flame photometrically, phosphate and sulphate by colorimeter, chloride by titration (chlor-o-counter). All methods that have been used for the above determinations have been described in manuals written for internal use only.

Table 1: Summary of fieldwork and laboratory activities

	BROAD SOIL LANDSCAPE I (Serengeti Plain)				BROAD SOIL LANDSCAPE II			BR.S.L.III	
	I.1	I.2	I.3	SUB-TOTAL	II.1	II.2	SUBTOTAL		TOTAL
SOILS									
Number of samples collected	437	310	424 (456)[1]	1171 (1203)[1]	35	170	205	6	1382 (1414)[1]
No of profiles sampled and investigated	71	45	56 (63)[1]	172 (179)[1]	9	18	27	1	200 (207)[1]
No of profiles of which samples had "partial" analysis[2]	35	19	20 (27)[1]	74 (81)[1]	4	1	5	1	80 (87)[1]
ditto "total" analysis[3]	36	26	36	98	5	17	22	-	120
No of soil pits dug	4	5	21	30	-	18	18	4	52
No of profile descriptions	3	4	7	14	-	3(11)[4]	3(11)[4]	1	18(26)[4]
No of profiles with data on CEC, exch.cations for various soil horizons	2	3	3	8	-	5	5	-	13
No of profiles with pF characteristics for various horizons	2	4	3	9	-	2	2	-	11
ditto with data on bulk density for various depths	2	4	5	11	-	3	3	-	14
ditto with data on infiltration on various horizons	4	4	4	12	-	2	2	-	14
No of "standard" profiles	2	4	4	10	-	1	1	-	11
No of "standard" samples[5]	14	20	23	57	-	5	5	-	62
VEGETATION SAMPLES[6]									
No of sites	2	5	12	19	-	12	12	-	31
No of samples	5	10	25	40	-	31	31	-	71
No of grass species involved	4	4	7	9	-	7	7	-	11
WATER SAMPLES[7]									
(rivers and lakes)	4	3	13	20	2	-	2	-	22

N.B. for notes 1-7, see next page

(notes on Table 1 on field and laboratory work)

[1]) sites selected and samples collected by K. Gerresheim; data obtained at the SRI soil lab.

[2]) "partial" analysis included: saturation percentage (SP), pH paste, pH saturation extract, EC_e with or without me/L (NO_3^-) and $CaCO_3$ percentage

[3]) "total" analysis: as "partial" analysis but with soluble salts (Na^+, K^+, $Ca + Mg^{2+}$, CO_3^{2-}, HCO_3^-, Cl^-, SO_4^{2-}) analysed in the saturation extract.

[4]) descriptions made by D. Herlocker or in co-operation with him.

[5]) on the standard samples the following additional determinations have been made at the Dept. of Soils and Geology:

- X-Ray diffractograms of the clay fractions (62 samples)
- elemental analysis of total soil and clay fraction (62 samples)
- mineralogy of clay fraction and coarse fraction (32 samples)
- CEC values of clay fractions (62 samples);
- qualitative test for allophanes (62 samples)
- textural analysis (56 samples) at the Laboratory for Soil and Crop testing (Oosterbeek)
- determination of % organic matter (Oosterbeek).

[6]) a part of the samples has been analysed on K, Na, Ca, Mg, P and Crude Protein (percentage of dry matter) at the laboratory for soil and crop testing at Oosterbeek; the other part on the same elements incl. Crude Protein and in addition on NO_3, Cl, SO_4, at the Dept. of Soils and Fertilizers at Wageningen.

[7]) about half of the number of samples has been analysed "totally" (pH, EC, soluble salts), the rest was only checked for conductivity.

3. Climate

3.1. Introduction

Until 1975 no detailed studies on the climatic conditions within the Serengeti Ecosystem have been made.
Like in many other parts of the African continent, rainfall (annual amounts, distribution) is the most important variable amongst the climatic factors that prevail in East Africa and also in the Serengeti Ecosystem.
Norton-Griffiths, Herlocker and Pennycuick (1975) described the distribution of the rainfall within the Serengeti Ecosystem during the year and the relationships between rainfall patterns on the one hand and major vegetation zones, distribution and movements of large herds of herbivores on the other hand.
The rainfall distribution during the year is marked by the succession a wet and a dry season. In the intertropical region the wet season rains are governed by the annual movements of the so-called intertropical convergence zone (ITCZ) in association with monsoon winds, resulting, for instance, into a two-peak wet season (Nieuwolt, 1977). Rainfall distribution across the ecosystem, however, is likely to be influenced by local effects, of which the presence of Lake Victoria (63000 km^2) in the west and the Crater Highlands (2000-3000 m altitude) in the east (rain shadow effect) are the most important.
The annual and seasonal rainfall patterns and their variability have been derived and calculated from monthly rainfall totals (mm) collected during the last 5-15 years from a large number of storage gauges all over the ecosystem; a limited number of stations provided data for periods of over 30 years.
Compilation of isohyet maps and the calculation of the variability have been done statistically using the trend surface analysis (TSA)

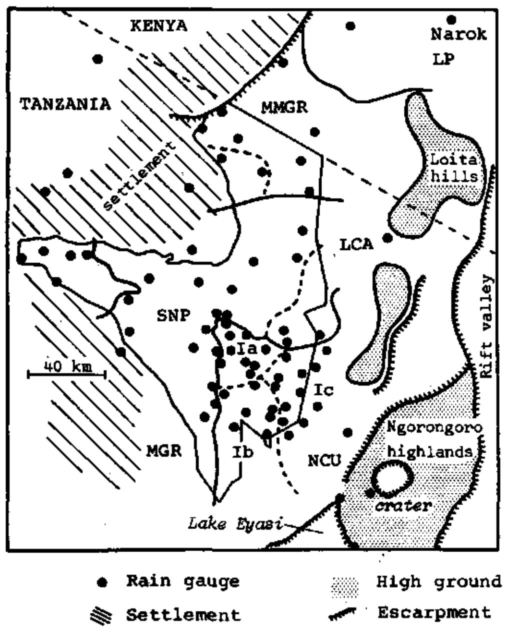


Fig.3a: Location and distribution of monthly rain gauges throughout the Serengeti Ecosystem (derived from Norton-Griffiths et al., 1975).

I	: Serengeti Plain	LP	: Loita Plain
Ia	: Long grasslands	MMGR	: Masai Mara Game Reserve
Ib	: Intermediate grasslands	LCA	: Loliondo Controlled Area
Ic	: Short grasslands	MGR	: Maswa Game Reserve
SNP	: Serengeti National Park	NCU	: Ngorongoro Conservation Unit

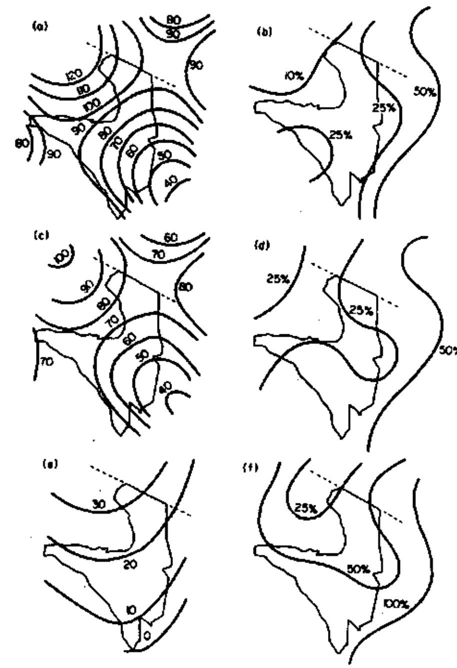


Fig.3b: Rainfall isohyet maps for the Serengeti Ecosystem. Annual total (a), annual variability (b), wet season total (c), wet season variability (d), dry season total (e) and dry season variability (f).
(a), (c) and (e) in cm; (b), (d) and (f) in %
(From Norton-Griffiths et al., 1975).

(Norton-Griffiths & Pennycuick, 1974; Norton-Griffiths et al., 1975). Fig.3a and 3b show the locations of the raingauges involved and the isohyet maps of annual, wet season and dry season rainfall and their variability within the Serengeti Ecosystem. Many of the gauges in the Serengeti Plain, for instance, have been installed by Braun (1973) in connection with his study on primary grassland production (1966-1970).

The mean annual rainfall across the Ecosystem was found to increase from 400 mm in the south-east (near the Crater Highlands) to 1200 mm in the north-west (Mara Region near Lake Victoria); the mean wet season rainfall shows the same gradients as the mean annual precipitation while the dry season rainfall increases from nearly 0 to 300 mm from the south towards the north (Mara Region). The variability was negatively correlated with the rainfall especially in case of the dry season rainfall. Mean annual rainfall appeared to be the lowest across the grassland covered Serengeti Plain: 400 mm in the south-east to 700 mm near the boundary between grasslands and woodlands. Norton-Griffiths et al. (1975) found that the yearly rainfall distribution pattern in the Plain differed significantly from patterns in the other parts of the ecosystem (Fig.4a), namely in the following respects:

- a more strongly marked dry season
- the lacking of a twin peak wet season rainfall: whereas in all other regions the rainfall shows a strong peak in April, the rainfall decreases gradually after the broad December-January peak (Fig.4a)
- the shift of the onset of the season from November (in the north-western part of the ecosystem) towards December in the south-east (Serengeti Plain). The latter could actually be observed in the field from the rain front progressing day by day from the north-

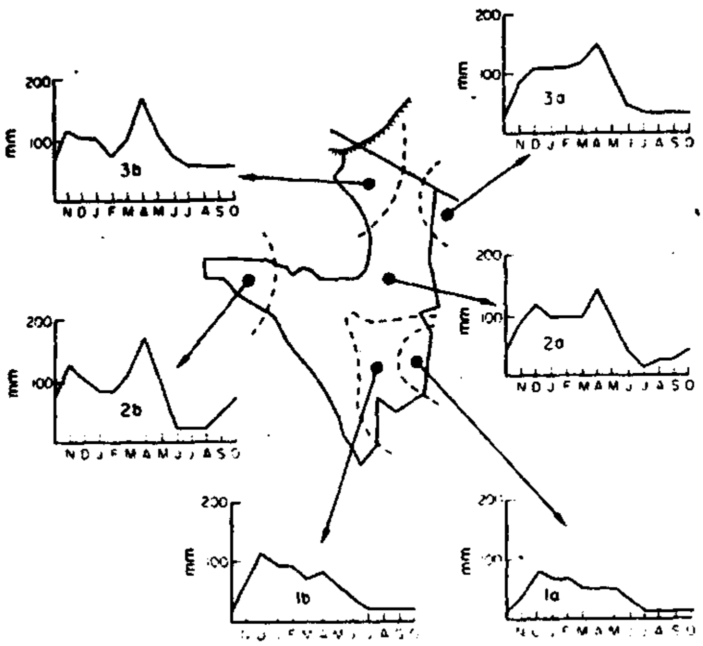


Fig 4a: The mean annual pattern of rainfall in 6 sub-groups
of raingauges. (From Norton-Griffiths et al.,1975)

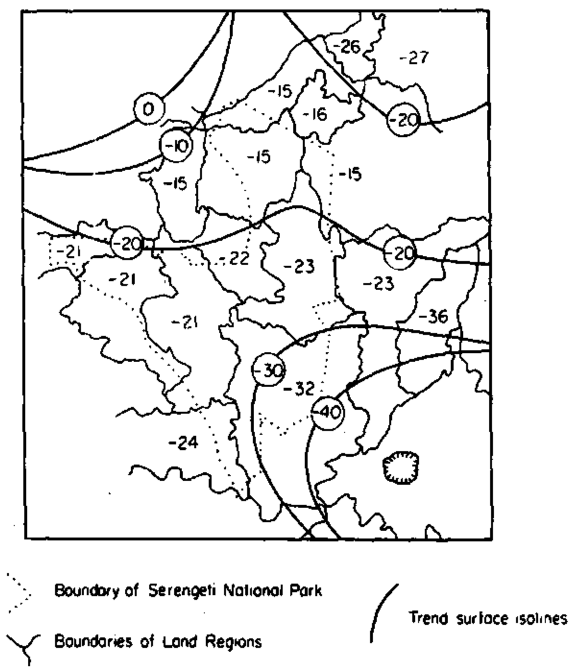


Fig 4b: Climate typing of the Serengeti Ecosystem according to
Thornthwaite's index; figures in circles refer to the
trend surface isolines. Other figures are those calcu-
lated for each Land Region (acc.to Gerresheim,1974).
(From Norton-Griffiths et al.,1975)

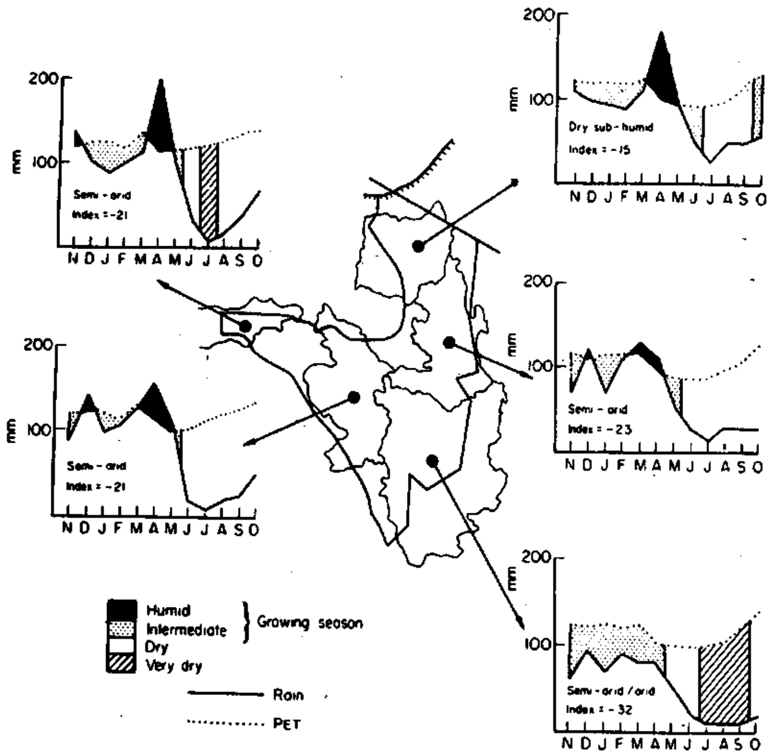


Fig 5a: Climatograms for 5 selected Land Regions

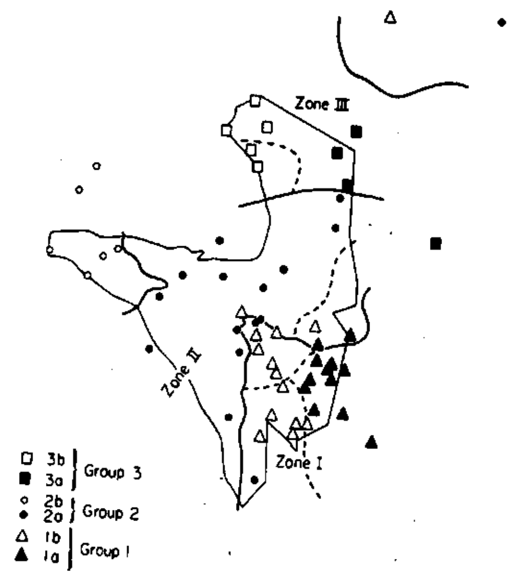


Fig 5b: The spatial relationship between groups and sub-groups of raingauges and the Serengeti's vegetation zones

Group 1: Grasslands of the Serengeti Plain (zone I)
- 1a: Short grasslands
- 1b: Long and Intermediate grasslands

Group 2: Acacia woodland zone (zone II)
- 2a: Acacia woodland
- 2b: Long grassland

Group 3: Combretum/Terminalia woodland (zone III) (evergreen / semideciduous)

Figures 5a and 5b derived from Norton-Griffiths et al.(1975).

west towards the south-east, followed by the greening of the grass vegetation - the rapid regrowth of the grasses was most evident in burnt areas as the so-called "green flush" - and the movements of the migratory herds towards the Serengeti Plain in the south-east.
Using Thornthwaite's index (Thornthwaite, 1948) for climatic typing Norton-Griffiths et al. (1975) have distinguished regional climatic zones within the Ecosystem ranging from arid ($I < -40$) in the south-eastern part near the Crater Highlands to moist sub-humid ($I > 0$) in the north-west (Fig.4b). For the various stations throughout the Serengeti Ecosystem, Norton-Griffiths et al. (1975) estimated the potential evapotranspiration (PET) - which was needed for the calculation of Thornthwaite's index - from the potential evaporation (PE). The latter, in its turn, was also estimated using the linear relationship between altitude and PE as found by Woodhead (1968 a,b) for stations throughout East Africa. The annual PET was estimated by multiplying the annual PE by a factor 0,75 according to Brown & Cocheme (1973).
Fig. 5a shows climatograms for five selected Land Regions according to Gerresheim (1974). The climatogram for the Plain differs strikingly from those belonging to the other Regions by the lacking of any water surplusses during the year, the short growing season and the prolonged very dry period from July until October. With regard to the relationship between climate and vegetation Norton-Griffiths et al. (1975) showed the spatial correlation between various rainfall patterns - indicated as raingauge groups and sub-groups - and major vegetation boundaries (Fig. 5b).
In view of the established correlation between rainfall patterns and major vegetation boundaries it is not surprising to find certain climatic isolines based on Thornthwaite's index (Fig. 4b) to coincide very well with boundaries between Land Regions: the -20 isoline

coinciding with the boundary between Acacia woodland (zone II) and Combretum/Terminalia woodland (zone III) and the -30 isoline, following the boundary between the Serengeti Plain (zone I) and the adjacent Acacia woodlands (zone II); for zones, see Fig.5b .

3.2. Rainfall patterns across the Serengeti Plain

In this paragraph data collected from stations in the grasslands of the Serengeti Plain and adjacent woodlands are discussed. The data have been collected between November 1968 and November 1973 (5 year period) by Braun (1973) from 1968 until 1970 and by Kreulen and the present author from 1970 until 1974 on behalf of their respective studies on primary grassland production, feeding of Wildebeest and soil/vegetation relationships.

Besides the collecting of rainfall data, some measurements have been made on air temperature, evaporation from an open pan and rainfall intensity (daily readings). From the temperature and daily rainfall data conclusions could be drawn with regard to the soil temperature and soil moisture regimes which are key factors for the classification of the soils according to Soil Taxonomy (1975).

3.2.1. Compilation of rainfall maps

The method for drawing the 50 mm isohyetal lines is given in Norton-Griffiths et al. (1975) as the "linear method". Herewith it is assumed that the rainfall gradients between neighbouring raingauges are proportional to the distance between them.

Of 22 gauges 5 year records were available, of 14 gauges 4 years; in the latter case mostly the figures of the first-very dry-year (1968-1969) were missing. These figures were deduced from a map, compiled from known figures of that year which also included data from some gauges outside the study area,by which a fairly accurate overall picture could be obtained. The ratios between wet season and dry season rainfall during that year were estimated from the means of the ratios of surrounding stations. Similarly, some monthly figures that were missing for a number of stations during the period November 1969 - November 1973 have been estimated from those of surrounding gauges. In case there was sufficient similarity between soil characteristics and floristic composition of the grassland vegetation at the sites concerned, a comparison of the monthly measured greenness of the grasses was also used for the estimation of missing data.

3.2.2. Discussion of the results

a. Rainfall distribution.

Norton-Griffiths et al. (1975) considered a "rainfall year" to cover the period between 1 November of one year and 1 November of the following year (instead of 1 January until 31 December). This period was chosen because it included the succession of a wet (November-May) and a dry (June-Oct.) season. The overall pattern shows an increase of rainfall from the east-south-east towards the west-north-west, viz. about 450 mm to 800 mm (near Seronera). The low rainfall in the eastern parts of the Plain is undoubtly due to the rain shadow effect of the Ngorongoro Crater Highlands. Most of the rain falls in the eastern parts of the Highlands by eastern to south-eastern winds; the Angata Salei Plain just at the western base of the highlands (left out from the map) is even dryer than the eastern Serengeti Plain.

The mean annual rainfall pattern (Fig. 6) shows several trends that reoccurred each year during the period of observations.

- a steep east-west gradient in rainfall found to the east of Naabi

Fig. 6 : Mean Annual Rainfall (mm) 1968 – 1973

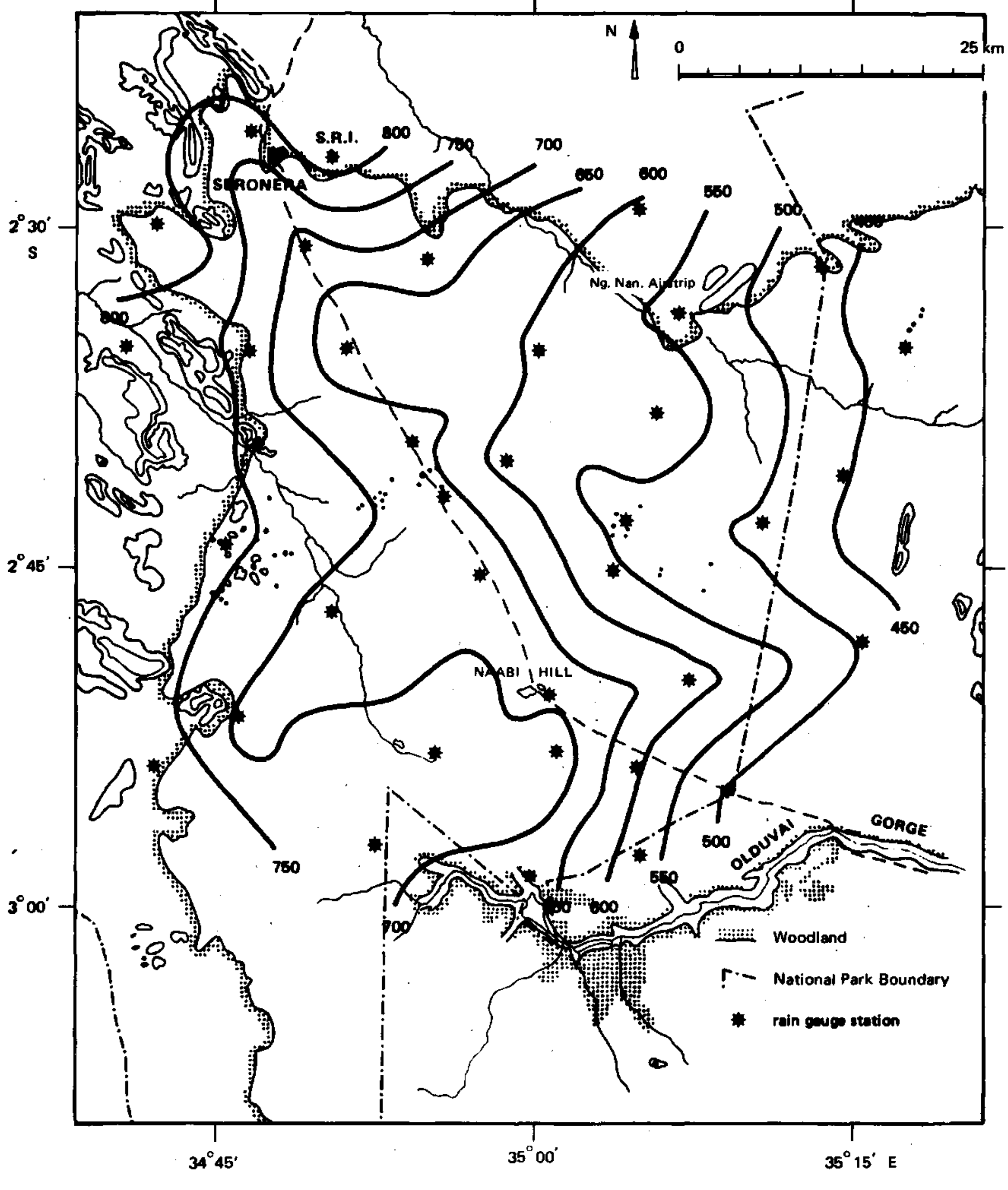


Fig.7a: Mean Wet Season Rainfall (mm) 1968 - 1973

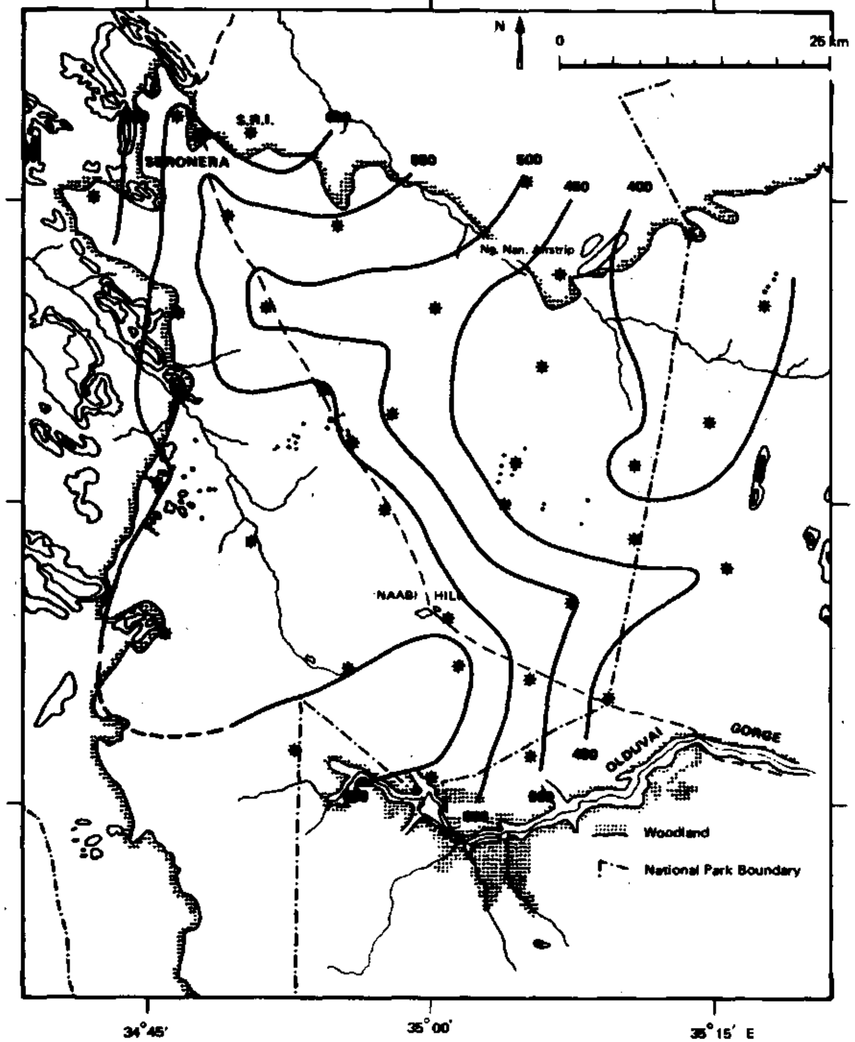
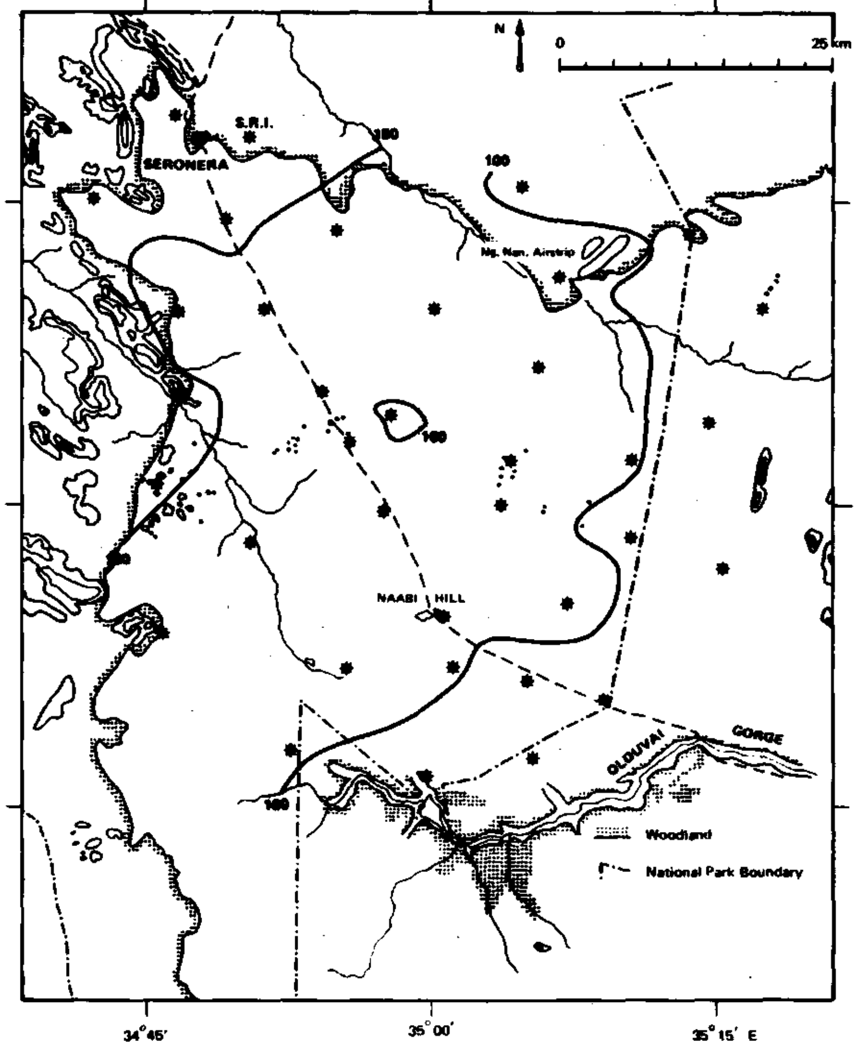


Fig.7b: Mean Dry Season Rainfall (mm) 1968 - 1973



Hill; the 600 mm isohyet coincides roughly with the sharp boundary between Short and Andropogon greenwayi grasslands.

- west of Naabi Hill a large area is found in which the gradients are very weak: it coincides with an area in which differences in elevation are small.
- the area in the northern part of the Plain, that extends from Lemuta Hill via the Barafu kopjes, Gol kopjes Zebra kopjes towards the Masai kopjes[1]) (Sersi station), is characterized by a very gradual increase of the rainfall. East of the Sametu kopjes[1]) mainly so-called "Short" grassland is found, west of these kopjes mainly "Long" grassland; the boundary between "Short" and "Long" grasslands is a gradual one. Besides the overall rain shadow effect of the Ngorongoro Crater Highlands on the annual rainfall, there might be an additional rain shadow effect across the northern part of the Serengeti Plain caused by the Gol Mountains and Lemuta Hill. The higher number of cloudless days compared to neighbouring areas (C.J. Pennycuick, pers. communication) seems to support this theory.
- in the north-western part of the Plain ("Long" grasslands) another steep gradient of increasing rainfall is found. This gradient coincides over a considerable distance with the grassland/woodland boundary that runs roughly from Seronera via the Olburturoto kopjes[1]) and Ngare Nanyuki towards Soit Ayai Park entrance.

The trends found on the basis of 5-year data described might be considered as local effects. The local effects described for the northern part of the Plain also showed up - although less marked - from a trend surface analysis on Plain-gauges only (10-year data, Norton-Griffiths, pers. communication). This was not the case for the steep gradients east of Naabi Hill and along the north-western

[1]) for location see Fig. 2b.

and northern edge of the Plain. The existence and the permanent character of these gradients seem to be proved by the sharp boundaries between soils (see Part II) and vegetation (viz. between Short and Intermediate grasslands, see Part III) coinciding with the gradients. The effects of the rainfall gradients on soil properties show up, for instance, from the good correlations that have been found between mean annual rainfall pattern and the distribution of salts and lime throughout the soil profiles.
The spatial distribution of the mean wet season rainfall (November until June) based on the 5-year records shows a pattern that strongly resembles that of the mean annual rainfall (Fig. 7a); the dry season rainfall was found to be nearly constant for the greater part of the Plain, viz. 100 mm - 150 mm from the south-east towards the north-west (Fig. 7b).

b. Rainfall intensity

The amount of rainwater that can be stored in a soil profile will not only depend on the total amount of rainfall but also on the infiltration characteristics of the top soil or layers at lower depths. This becomes of special importance if the topsoil has a surface crust or if dense soil layers such as a natric horizon occur at shallow depth. If the rainfall intensity (mm/h) exceeds the infiltration rate (for measurements see part II), the excess of rainwater will run off; standing water on the surface occurs only very locally since the topography in most parts of the study area is very gently sloping or undulating.
Daily rainfall records kept by the present author at the Serengeti Research Institute during a period of 3 consecutive years (1970-1973), showed that roughly 75% of both the totals of wet season and dry season rainfall occurred as cumulative falls per day of over 10 mm,

and more than 50% as cumulative falls of over 20 mm. A summary of the monthly data as well as some figures derived from these data can be found in Appendix 1 . For the first 5 classes (0-5 mm, ..., 20-25 mm), the amounts of the total rainfall over three years appeared to be fairly constant whereas there was a sharp rise for the class of over 25 mm. The highest daily falls amounted 83 mm (14-4-1971), 74,3 mm (2-10-1971) and 61,7 mm (7-11-1972). Such high amounts and in general most daily falls over 25 mm, fell usually within a few hours as heavy rainstorms, and run-off was recorded all over the area. Measurements of the depths to which rainwater had penetrated on such occasions showed a run-off of 25 to 75% of the total amount of rain. There appeared to be significant differences in penetration depth between soils that supported different vegetation types and that were due to differences in infiltration rate of the soils: the infiltration rate appeared to be low in soils with a sparse cover of short grasses (these soils had often a natric horizon at shallow depth), whereas a much higher infiltration rate was found in soils covered by tall grasses and herbs or below trees and shrubs. The latter soils received - besides the precipitation - considerable quantities of rainwater in the form of run-off. Some more attention to this aspect will be paid in Part III: Vegetation and Soils.

In view of the high rainfall intensities that occur in the study area, often resulting into high amounts of run-off, and considering the large differences in infiltration rate that exist between the various soil types, their effects on the actual storage capacity of the soils should be handled with care in calculating Thornthwaite's index and in constructing climatograms.

Norton-Griffiths et al. (1975) used - partly on the advice of the present author - for their estimations a water storage capacity of 100 mm for all soils throughout the Serengeti Ecosystem. Although the factors rainfall intensity and infiltration rate were known to be relevant in this respect, their effects on the storage capacity of soils in different areas may well have been underestimated.

c. Soil Moisture Regime

Soil Taxonomy (1975) defines the Soil Moisture Regime (SMR) as "the presence or absence either of groundwater or of water held at tensions of less than 15 bars in the soil or in specific horizons by periods of the year". If soil moisture is held at tensions over 15 bars the soil is considered as dry, if held at tensions less than 15 bars the soil is called moist.

In Soil Taxonomy (1975) the SMR forms a differentia to the classification of soils up to the highest levels.

A number of classes of moisture regimes has been distinguished depending on the moisture regime in the so-called Soil Moisture Control Section (SMCS) of a profile throughout the year. The moisture regime in the SMCS can be derived from climatic data (rainfall!). The upper boundary of the SMCS is the depth to which the dry soil will be moistened by 25 mm of water within 24 hours, the lower boundary is the depth to which the dry soil will be moistened by 75 mm of water within 48 hours; the lower boundary may also be formed by the upper boundary of a lithic or paralithic contact, a petrocalcic horizon etc. For soils with particle sizes fine loamy coarse and fine silty or clayey, the upper and lower boundaries of the SMCS lie roughly at respectively 10 and 30 cm. For most of the soils of the Serengeti Plain the soil moisture regime could be characterized as Ustic: "The soil moisture control section is dry in some or all parts for 90 or more cumulative days in most years. But the moisture control section is moist in some parts for more than 180 cumulative days or it is continuously moist for at least 90 consecutive days"; in view of the latitude of the study area - appr. $2^{o}20'$ - $3^{o}00'$ south - the mean annual soil temperature was estimated to be 22 ^{o}C or higher, while the mean summer and winter soil temperatures were thought to differ by less than 5 ^{o}C at 50 cm depth.

Assuming that a monthly rainfall of 50 mm will moisten at least the upper part of the soil moisture control section, monthly rainfall data, collected over a period of 10-13 years for stations on the Serengeti Plain (data available at the Serengeti Research Institute), indicate that in most places the SMCS will moist in some part for 180 cumulative days indeed. In most years the entire moisture control section may be moist for even 90 consecutive days. The situation at the Olduvai station (in the south-eastern part of the Short grasslands), however, tends to grade towards an <u>Aridic</u> moisture regime: "In most years there is no available water in any part of the SMCS more than half of the time (cumulative) that the soil temperature is over 5 ^{o}C; and there is no period as long as 90 consecutive days when there is moisture in some or all parts of the SMCS while the soil temperature at 50 cm is continuously above 8 ^{o}C" (Soil Taxonomy, 1975). The dry season at the Olduvai site lasts longer than at the sites that lie further westwards,while the monthly falls during the wet season seem just sufficient to moisten the upper part of the SMCS to the required moisture content.

The mean annual and monthly rainfall figures for Olduvai are also considerably lower than those for stations in the part of Short grasslands that lies further westwards inside the boundaries of the study area. The more arid moisture regime at Olduvai (closer to the Crater Highlands, stronger rain shadow effect) shows up from the sparser short grass vegetation - also overgrazing by cattle may contribute to the lower cover - from the presence of free calcium carbonate up to the soil surface and from the shallow depth (20-30 cm) at which a petrocalcic horizon is found in level areas with little or no erosion. Within the study area the petrocalcic horizon occurs under comparable circumstances at depths varying between 50 and 100 cm, while a decalcification of the topsoil is found increasing from the south-east towards the north-west (see also Part II, discussion of characteristics of the soils within soil Landscape I.1).

3.3. Evaporation

Woodhead (1968 a, b) estimated the monthly potential evaporation from open water (E_0) for Kenya and Tanzania.
Woodhead considered the major contribution to the E_0 to come from the incoming solar radiation. Table 2 shows monthly evaporation data - quoted from Woodhead (1968b) - for some stations situated around the Serengeti Ecosystem and open pan evaporation data for the SRI near Seronera, collected by the present author between 1971 and 1974.
The Woodhead data show a clear increase of the annual and monthly E_0 with a decrease of altitude: 1403 mm at Ngorongoro (2300 m) to 2056 mm at Musoma (1150 m) on the shore of Lake Victoria.
The evaporation estimated for the Ngorongoro and Mbulu stations showed a marked variation during the year; the evaporation reaches the highest values between September and April with peaks in October/November and February/March. At Musoma the seasonal fluctuations were less pronounced due to the special climatic conditions that prevail near the Lake.
For the region, in which the study area is situated, a mean annual E_0 of about 1900 mm was estimated from Woodhead's maps. The latter amount corresponds with the mean annual evaporation measured from an open pan at the SRI[1]) between 1971 and 1974 (Table 2). For the

[1]) The evaporation pan was made out of a 35 x 25 x 25 cm storage tin; the tin, which had been placed at a depth of 10 cm, was filled up to appr. 250 mm (appr. 10 cm from the top) and protected against drinking by wild animals by a cover of fine-mesh wire netting. Measurements of the evaporation were made every 2 or 4 weeks by checking the water level with a dip stick. After measuring, the pan was refilled up to the original level.

Table 2 Monthly and annual evaporation from open water (E_o) according to Woodhead (1968b) and evaporation from an open pan (E_p), measured at the SRI.

	Jan.	Febr.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	period	total evap. per annum (mm)	mean daily evapo-ration (mm)
Musoma (1150 m)															
E_o (mm/month)	178	166	181	156	159	160	165	179	186	189	166	171	1955-1964	2056	5.63
E_o (mm/day)	5.74	5.87	5.84	5.20	5.13	5.33	5.32	5.77	6.20	6.10	5.53	5.52			
Mbulu (1530 m)															
E_o (mm/month)	169	165	171	133	108	118	119	139	167	187	160	165	1946-1954	1801	4.93
E_o (mm/day)	5.45	5.84	5.51	4.43	3.49	3.93	3.83	4.48	5.57	6.03	5.35	5.32			
Ngorongoro (2300 m)															
E_o (mm/month)	121	122	139	119	98	98	86	99	121	134	141	125	1964	1403	3.84
E_o (mm/day)	3.89	4.21	4.48	3.95	3.15	3.26	2.79	3.20	4.03	4.31	4.71	4.03			
SRI (1545 m)															
1971 E_p (mm/month)	90	131	123	137	116	141	133	146	186	156	205	157	1971	1721 (357d.)	4.82
E_p (mm/day)[1]	4.29	4.68	3.97	4.57	3.63	4.41	4.75	4.71	6.20	5.03	6.83	4.76			
1972 E_p (mm/month)	165	114	152	161	104	120	164	166	178	167	158	131	1972	1780 (364d.)	4.89
E_p (mm/day)[1]	5.50	4.22	4.90	5.03	3.47	4.00	5.29	5.35	5.93	5.39	5.27	4.23			
1973 E_p (mm/month)	108	146	132	155	136	161	239	171	164	160	142	105	1973	1819 (358d.)	5.08
E_p (mm/day)[1]	3.48	5.21	4.13	5.34	4.53	5.37	7.71	5.53	5.47	5.16	4.74	4.19			
1971-1973 E_p (mm/month)[2]	137	132	134	149	120	138	185	161	176	161	168	137	1971-1973	1798 (365d.)	4.93
Mean E_p (mm/day)	4.43	4.71	4.33	4.98	3.87	4.59	5.96	5.19	5.87	5.19	5.61	4.42			

1) E_p (mm/day) estimated by dividing the evaporation measured over a period of about 1 month by the number of days of that period.

2) Evaporation for each month calculated from its mean daily evaporation.

latter station there were also clear seasonal fluctuations like those found for Mbulu and Ngorongoro. The period, however, in which the higher values occur, seems - using the mean monthly values - to extend from July until January, i.e. the greater part of the dry season (June-November) and the short wet season (November- December). Considering the data throughout the year,high daily values appeared also to occur in January, February and April (1972, 1973). In spite of the considerable variations in mean daily evaporation during the 3 years of observations, the yearly totals were fairly constant.
The data collected at the SRI show that the period marked by the stronger evaporation largely coincided with the dry season (June-October). This could be caused by the advection of very dry air carried across the Serengeti Plain by the strong easterly winds that prevail during the dry season.
In 1969/1970 Braun measured the evaporation from an open pan for several stations, a.o. SRI, NaZu (Intermediate grasslands, 5 km south-east of Naabi Hill) and BARSEK (Short grasslands, near the Park boundary); Braun obtained the following results:

Station	altitude	period	total evaporation (mm)	mean daily evaporation (mm)
SRI	1545	8-12-'69/4-11-'70	1933	5.82
NaZu	1650	30-10-'69/2-11-'70	1845	5.01
BARSEK	1800	13-11-'69/3-11-'70	2086	5.88

Regarding the evaporation found at the SRI, the figure found for NaZu appears to fit the relationship between evaporation and altitude as found by Woodhead (1968 a,b). However, the evaporation at BARSEK (about 250 m higher in elevation!) seems at least to equal the evaporation measured at the SRI. The high evaporation found for the BARSEK station might be due to local effects, viz. a stronger advection effect (stronger winds) and a lower relative humidity (BARSEK lies closer near the Crater Highlands). The latter finding could imply that the evaporation in the eastern part of the Serengeti Plain - i.e. the zone of the Short grasslands - may be higher than the values estimated by Norton-Griffiths et al. (1975), which would result into a stronger degree of aridity for this area than the calculations of Thornthwaite's index did produce (Fig.4b).

3.4. Temperature

During three years (1970-1973) measurements on maximum and minimum temperature of the air have been by the author at the SRI. A summary of the data is found in Table 3 .

Mean monthly maximum temperatures varied from 26.6 to 30.6 °C, mean monthly minima from 13.1 to 16.4 °C. Mean highest maxima and minima did occur in the period between November and May, i.e. the wet season; mean lowest maxima and minima were measured between May (June) and August, i.e. the dry season when the cloud cover is high. March was found to be the hottest, July to be the coldest month. During the year the tendency of a 2-peak temperature curve showed up: maxima in November and March, minima in June/July (dry season) and - less clearly - also in February (short dry season).

The daily maxima occurred around 2 p.m., the minima at 5-6 a.m. Highest temperatures measured were 34.5 °C in March and April 1973, the lowest temperatures were recorded in July 1973: 10.0 °C. Higher and lower temperatures had been recorded before (Braun, pers.comm.). The mean annual maximum temperature was 28.7 °C, the mean annual minimum 15.2 °C. The mean daily, monthly or annual temperatures could not be derived from the mean maxima and minima values - e.g. by taking the mean values - since daily fluctuations showed a marked peak for the maximum temperature in the early afternoon and broad traject of low temperatures during the night and the early morning. Eventual seasonal influences have been left out of consideration. The average of the mean annual maximum and minimum at Seronera amounted 21.9 °C; the mean annual temperature will probably be somewhat lower.

Table 3 also gives the mean monthly temperatures measured at various stations outside the Serengeti Ecosystem (derived from Woodhead, 1968b). The figures from the Musoma Station differ strikingly

Table 3 Mean monthly and annual air temperatures

Station	altitude	Mean monthly temperatures (°C) Jan.	Febr.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Period	mean annual temperature (°C)
Musoma[1])	1150 m	23.3	23.6	23.6	23.1	23.0	22.5	22.2	22.5	23.2	23.8	23.4	23.1	1955-1964	23.1
Arusha (airf.)[1])	1390 m	20.2	20.8	21.0	20.2	18.8	17.8	16.6	17.5	18.6	20.0	20.2	20.2	1955-1964	19.3
Mbulu[1])	1530 m	18.9	19.1	19.4	19.7	17.2	16.0	14.8	15.8	17.8	18.5	19.2	19.1	1946-1954	18.0
Loliondo[1])	2100 m	16.5	16.9	17.4	16.7	15.1	14.8	14.3	14.9	15.9	16.8	16.9	16.4	1948-1953	16.0
Ngorongoro[1])	2300 m	14.3	16.0	16.7	14.4	12.9	12.7	11.1	11.7	12.8	13.4	14.7	14.2	1964	13.7
SRI	1545 m														
mean monthly maxima[2])		29.3	28.9	30.6	29.2	27.1	26.6	27.2	28.1	29.2	29.8	29.5	28.8	1971-1973	28.7
mean monthly minima[2])		15.9	16.0	15.9	16.4	15.2	13.8	13.1	13.6	14.7	15.6	16.2	15.7	1971-1973	15.2
average		22.6	22.5	23.2	22.8	21.1	20.1	20.1	20.9	22.0	22.6	22.8	22.2	1971-1973	21.9

1) derived from Woodhead (1968b)

2) calculated from daily records

from those of the other stations by the only very weak seasonal fluctuations, probably due to special climatic conditions that prevail along the shore of Lake Victoria. Data from the other stations also show a distinct colder period coinciding with the dry season, whereas highest temperatures occur during the wet season.

On the basis of the relationship between air temperature and altitude one would expect comparable data for the Mbulu (south of the Crater Highlands) and the SRI stations. For the latter station, however, the difference between mean summer and mean winter temperature (N.B. means of maxima and minima!) is less marked than for the Mbulu station and for the Arusha, Loliondo and Ngorongoro as well. The temperature regime at Seronera might be influenced by the temperature regime around Lake Victoria.

In the more easterly parts of the study area the temperatures are likely to be lower because of the higher elevation (1800 m) and - probably more important - because of the transport of cooled air from the Ngorongoro Crater Highlands by easterly winds; in the Highlands even night frost may occur during the dry season. Mean annual temperatures may be around 15-17 ^{o}C. Also the fluctuations between "winter" and "summer" temperatures will be greater, and may resemble those of the temperature regime in the Ngorongoro Crater Highlands.

<u>Soil temperature regime</u>

In Soil Taxonomy (1975) the soil temperature regime is used as a differentia , for the classification at various levels. Most relevant in this respect are the mean annual soil temperature and the difference between the mean "summer" and mean "winter" temperatures in the soil at a depth of 50 cm.

In the intertropical region the mean annual soil temperatures vary with elevation, while the seasonal soil temperature fluctuations largely depend on cloud cover and rain. The mean "winter" and "summer" temperatures at 50 cm depth differ usually by less than 5 °C. According to Soil Taxonomy one can estimate the mean annual soil temperature by adding 1 °C to the mean annual air temperature. The average summer temperature of the upper 100 cm can be approximated by subtracting 0.6 °C from the mean summer air temperature. Mohr, Van Baren and Van Schuylenborgh (1972) mention soil temperatures. measured in Indonesia, to be even 2.0 - 4.5 °C higher than the air temperature. Soil Taxonomy (1975) distinguishes 5 mean annual soil temperature classes to which the prefix "iso" may be added in case the mean soil winter and summer temperatures differ less than 5 °C (intertropical region!).

On the basis of the known data on air temperature measured at the stations mentioned in Table 3 and on the basis of the soil air temperature relationships mentioned before, the following temperature classes are considered to be relevant:

Isomesic: Mean annual soil temp. 8 °C or more but less than 15 °C: Ngorongoro Crater Highlands.

Isothermic: Mean annual soil temp. 15 °C or more but less than 22 °C: Mbulu, Loliondo (Arusha).

Isohyperthermic: Mean annual soil temp. over 22 °C: Musoma (Lake Victoria shore).

In the eastern and central parts of the Serengeti Plain the soil temperature regime is more likely to be isothermic; considering the air temperature data obtained at the SRI and the increased mean air temperatures near Lake Victoria the soil temperature regime may grade from isothermic in the eastern part of the Plains to isohyperthermic in the western and north-western parts.

4. Geology

4.1. Stratigraphy and distribution of the most important formations

The geological formations that form the basic structure throughout the Serengeti Ecosystem consist of Pre-Cambrian basement rock. In the greater part of the Serengeti Plain the Pre-Cambrian rocks are overlain by a cover consisting of various layers of eolian tuffs of Pleistocene up to Holecene age which have been deposited during periods of strong volcanic activity (eruptions) in the Ngorongoro Crater Highlands.

Detailed information about the location of the most important geological formations within the study area and its direct surroundings can be found on the geological Map of Tanzania Quarter degree sheets 25 (Seronera) and 26 (Soit Ayai) surveyed by Macfarlane (1967, 1968), from the Geological Survey of Tanganyika, Quarter degree map sheets 37 (Moru) and 38 (Oldoinyo OGol) surveyed by Pickering (1960, 1958), and sheet 39 (Angata Salei) by Guest et al. (1961).
Locations and names of hills and other topographic features can be found in Figures 1 and 2b and on the soil map (Appendix to Part II).

a. The Pre-Cambrian Basement

Using classification of the Pre-Cambrium as given by Furon (1963) the following formations can be distinguished within the study area:

1. Middle Pre-Cambrium (3000-2000 million years B.P.): Nyanzian and Kavirondian; dominant rocks are: quartzites, sandstones and schists.

2. Late orogenic and intrusive rocks: granitic and gneissic rocks.

3. Terminal Pre-Cambrium (1000-600 million years B.P.): Bukoban, mainly consisting of quartzitic rocks.

1. Middle Pre-Cambrium: Nyanzian

Along the north-western boundary of the ash covered Serengeti Plain some exposures consisting of metavolcanic rock (meta-rhyolite, meta-rhyo dacite, meta-dacite and meta-andesite) are found e.g. Yarogaria Hill, along the southern slope of Nyaraswiga Hill and the eastern slopes of Kamunyo and Kianguge Hill. A few more exposures occur in the Old. Rongai range and south of the Losiurai range and consist mainly of banded "ironstones" and "ironstones".

In the eastern part of the study area the Oldoinyo OGol Hills - usually called Gol Mountains - are found. The formations consist for the greater part of Quartzo-felspathic and biotite gneisses and Quartz-mica schists in many places overlain by reddish quartzites (Kissele Quartzite) and have been defined by Pickering (1958, 1960) as the Oldoinyo OGol Group.

Some flat-topped hills are covered by a layer of volcanic ash of recent age. West of the Gol Mountains many groups of small and also a few large inselbergs are found scattered over the Serengeti Plain; according to Pickering (1958, 1960) they belong to the Serengeti-Group. Most of them belong to the upper formation indicated by the name of Sametu Gneisses (Quartzo felspathic, migmatic in part). Important groups of inselbergs or kopjes are the Gol kopjes - which also include the so-called "Zebra" and "South-east" kopjes - which are found near the centre of the study area, the Barafu kopjes and the Soguna kopjes in the north-east and the clusters of kopjes west and south of Lemuta Hill. Especially in the 3 former groups, many of the larger kopjes are located on top of the ridges, forming lines of kopjes that roughly have a north-south orientation. The largest inselberg of the subgroup of Sametu Gneisses is Naabi Hill; it is also located on the top of a long ridge and forms a striking feature within the landscape of the Serengeti Plain as it can be observed over large distances.

Other exposures of the Sametu Gneisses are found at the bottom of some deeply incised valleys: Magungu River and side arms (e.g. south of the Soguna kopjes and west of the Barafu kopjes), the Olduvai Gorge between Lake Ndutu and the place where the Seronera-Arusha road crosses the Gorge ("Olduvai crossing").

The lower formation of the Serengeti Group is constituted by Lemuta Hill, which consists for the greater part of quartzite and quartz schists. Along the eastern Park boundary 2 kopjes ("Maerua kopjes") are found that consist of basic rock, in which respect they differ strikingly from all other (acid) kopjes mentioned before.

In the north-western part of the Serengeti Plain a number of low <u>quartz hills</u> (whitish rock) are found: four hills along the Seronera River, one small hill just south of Mukoma Hill, classified by Pickering (1958, 1960) as Nyanzian; several outcrops of quartz or quartzitic rock are found on ridges e.g. opposite Oldoinyo Rongai along the Moru track, along the Gol kopjes track and along the Seronera-Loliondo track (white quartz pebbles on the tracks!).

It is not clear whether all the quartz hills or quartz ridges in the study area belong to the Nyanzian formations; they could also be quartz reefs comparable with quartz reefs or floats that are commonly found in the late orgenic or intrusive granitic rock elsewhere in the study area.

2. Late orogenic and intusive rocks

Late orogenic granitic rock and gneisses (recrystallized granitic rock), probably of Nyanzian-Kavirondian age, form the basic structure of the Dissected Plain which bounds the Serengeti Plain in the north; the area is covered by woodland or wooded grassland. Rocks consist of biotite leucogranites and granodiorites, porphyric granites and granodiorites, changing into various types of gneisses (recrystallized granitic rocks) in the east near the eastern Park boundary; locally quartz reefs are found (e.g. near Seronera). Soils have derived from the Basement material (residual soils) but they have been influenced to a lesser (western part) or greater extent (eastern part) by recent volcanic ash falls; in the eastern part some ridges are entirely covered by a layer of volcanic ash, namely near the boundary with the Serengeti Plain.

In several places thick layers of petrocalcic material, often marked by a cavity structure - "secondary limestone derived from calcareous tuff" according to Macfarlane (1967,1968) - are found exposed along river courses, but also on some ridgetops at eroded spots, especially near the boundary between woodland and the grass covered Serengeti Plain.
The secondary limestone has probably derived from tuffs of Pleistocene age and are different from the petrocalcic horizons that are found in the more recent ash deposits (Late Pleistocene-Holocene),that cover several ridge tops in this area, and in the ash cover of the Serengeti Plain.
Various types of granite and granodiorite-indicated by Pickering (1958, 1960) as Intrusive Rocks-outcrop along the steeper slopes and escarpments of the flat-topped hills that form the natural western boundary of the Serengeti Plain: in the Oldoinyo Rongai

range, the Nyaraboro Hills and the greater part of the Itonjo Hills the outcrops are facing the north and north-east, in the hills that lie further to the south - parts of the Itonjo Hills, Oldoinyo Olobaie - the granite is found exposed along the southern slopes; granitic rock is found exposed over a large area between the Losiurai range and the Simiyu River.

The granite occurs abundantly in the western half of the Serengeti Plain as Inselbergs - generally called "kopjes" - protruding through the ash layer that covers the Serengeti Plain. Most important are the Moru kopjes with large outcrops of over 50 m high, and the Simba kopjes in the Girtasho area. Other important clusters of kopjes are the Soit O Gnum kopjes in the south-western part of the Plain near Oldoinyo Olobaie and the Masai kopjes in the north-west. Some groups of kopjes are situated on top of the ridges (e.g. the Masai kopjes), others are found in all possible topographic positions.

Outcrops of granite are also found exposed in some parts of the valleys of the Mbalageti River and its tributary, the Oltuka River.

3. <u>Terminal Pre-Cambrium: Bukoban</u>

Bukoban formations are found in the hills along the north-western and western boundary: the northern slope of Nyaraswiga Hill, the western slope of Kamunyo and Kyanguge Hill, the Oldoinyo Rongai range, the Nyaraboro Hills, Itonjo Hills, etc. Purplish or grayish quartzites (Kinenge quartzites) are the dominant rock type, overlying Nyanzian rocks in the north and granitic rocks in the south (starting from the Oldoinyo Rongai range).

b. The Pleistocene and Holocene (Neogene)[1])

Pleistocene rocks or sediments are mainly found exposed outside the study area, viz. in the Ngorongoro Crater Highlands (Fig. 1). To the west the Crater Highlands are bound by the ash covered Angata Salei (an eastern extension of the Serengeti Plain) to the east by the Gregory Rift Valley.

Ashes ejected by the volcanoes during the Pleistocene have determined the present shape of the landscape of the Serengeti Plain.

Most important volcanoes are Ngorongoro, Lemagrut, Sadiman, Olmoti, Elanairobi, Mosonik, Kerimasi and Oldoinyo Lengai. Of these volcanoes Oldoinyo Lengai is still active; the others have become extinct already hunderd thousands of years ago. Three of the now extinct volcanoes formed calderas: the Ngorongoro Crater with an average diameter of 20 km, the caldera of Elanairobi or Embagai Crater (7-8 km diameter), which has a crater lake of considerable depth , and the 6 km wide Olmoti caldera.

The Crater Highlands have entirely been covered by volcanic extrusives. Guest et al. (1961) distinguish older extrusives (undifferentiated) and younger extrusives. The older extrusives and ejecta (lava's and tuffs) have originated from Ngorongoro, Lemagrut, Sadiman, Olmoti and Elanairobi. The eruptive phases during which the older extrusives have been deposited have been dated between (16.3-)2.8 to 1.65 million years B.P. (Hay, 1976).

This period of volcanic activity coincided with major changes in the landscape due to faulting, during which the Rift Valley obtained its present shape. The younger extrusives have originated from the strongly dissected and eroded Mosonik, which lies on the Rift Valley

[1]) acc. to the stratigraphic classification by Guest, James, Pickering and Dawson (1961).

escarpment west of Lake Natron, the slightly eroded Kerimasi, which lies right on the Rift Valley escarpment and the little eroded, still active Oldoinyo Lengai which is situated at the bottom of the Rift Valley just to the east of the northernmost extension of the Crater Highlands (Fig. 1).
Eruptive phases of Kerimasi have been dated between 1.1 - 0,4 million years B.P., deposits from Oldoinyo Lengai from 60.000 years ago up to the present.

Hay (1976) gives detailed information about lithology and mineralogy of the older and younger extrusives and ejecta; a summary is given on pages 12 and 13 of his book. A few characteristics of his data have been summarized in the following:

- Older extrusives: non-porphyric to porphyric (soda) trachyandesites and olivine basalts (Ngorongoro, Lemagrut), melilite tuffs and porphyric nephelinite lava (Lemagrut), porphyric nephelinite and nepheline phonolite (Sadiman). The Olmoti extrusives correspond largely with the rocks that have already been mentioned for Ngorongoro; in addition trachyte tuffs have been recorded, of which the glass had altered into zeolites (principally chabazite).
- Younger extrusives: (lithic) tuffs, volcanic conglomerates, Nephelinites, phonolithic and nephelinitic lavas and tuffs (Mosonik, Kerimasi, Oldoinyo Lengai according to Guest et al., 1961) with nepheline, melilite and (sodic) augite as the dominant minerals in the rocks of Kerimasi and Oldoinyo Lengai (Hay, 1976). Of special interest are the occurrence of carbonatites (Kerimasi, Mosonik), carbonatic rock and gray calcareous tuffs (Kerimasi, Oldoinyo Lengai) and recent deposits of almost pure sodium carbonate and bicarbonate in the crater of Oldoinyo Lengai. These deposits might have originated from successive intrusions of Na, Ca and K carbonatite magma into the granitic basement rock by

which the silica saturation of the basement rock decreased after each phase of intrusion (Dawson, 1962). Observations, made during this century, show that sodium carbonate ashes have been ejected from Oldoinyo Lengai several times since 1917, while sodium carbonate lava was extruded once in 1940 (Hay, 1976).
The ashes and tuffs, ejected during the periods in which the volcanoes of the Crater Highlands were active, have spread over the Serengeti Plain, transported by easterly and north-easterly winds that prevailed throughout the Pleistocene up to the present time. Evidence for the latter appeared from the distribution of ash and tuff layers as found in the Beds I-VI of the so-called Olduvai Sequence, which forms a nearly complete record of the period between 2.1 million years ago to the present (Hay, 1976).
The Olduvai Beds[1)]- which have a maximum thickness of about 100 m - are famous for their richness in fossile remains of mammals and ancient hominids and contents of artefacts used by early man.
Bed I is the oldest, Bed VI represents the youngest deposits.
Beds I, II, III and IV consist of lavas and deposists of eolian tuffs and ashes, or tuffs and ashes reworked by water,that had been ejected by the volcanoes of the Crater Highlands during periods of strong activity. The eolian and fluvial deposits were laid down in or around a saline-alkaline lake, much alike the present soda lakes in this region (L.Natron, L.Ndutu, L.Eyasi): lake deposits, lake margin deposits and alluvial fan deposits.
Bed I deposits and the lower part of Bed II originated during the eruptive phase of Olmoti, the upper part of Bed IV or Masek Beds consists of tuffs and ashes from Kerimasi. The age of the Masek Beds is estimated at 0.6-0.4 million years B.P.
The Masek Beds are overlain by the so-called Ndutu (lower and upper Ndutu Beds) and Naisiusiu Beds of Bed V.

1) exposed in the eastern part of the Olduvai Gorge.

During the periods in which the Ndutu Beds were deposited, the erosion of the Gorge did start. The lower Ndutu beds (sandstone, conglomerate and tuff) have presumably been deposited between 400.000 and 60.000 years B.P., those of the upper Ndutu Beds between 60.000 and 32.000 years B.P. (Hay, 1976). The earliest deposits of the lower Ndutu Beds may still have originated from Kerimasi, the later deposits did certainly originate from Oldoinyo Lengai. According to Hay the ashes, that formed the upper Ndutu Beds in the Olduvai Basin, had spread widely north and westwards (easterly winds!) over the Serengeti Plain covering an area of at least 15.000 km^2, i.e. an area that was considerably larger than the Serengeti Plain in its present size.

Between 22.000 and 15.000 years ago - at this time the Olduvai Gorge had attained its present shape - the Naisiusiu Beds have been deposited. Like the upper Ndutu Beds they consist mainly of aeolian tuffs. At present, deposits of these Beds, reworked by erosion processes, are found at the bottom of the gorge, while remnants of the original deposits are still present in many places along the sides of the gorge and occur as a thin layer over the adjacent Serengeti Plain, overlying the upper-Ndutu tuffs.

In the Olduvai sequence Leaky (1951) had already distinguished Bed VI, which consists of volcanic ash - known as Namorod Ash - erupted by Oldoinyo Lengai some 1200-1300 years ago. In the Olduvai Gorge the Namorod ash is found as valley bottom deposits, that have mostly been reworked; out on the Serengeti Plain the Namorod Ash overlies Naisiusiu deposits.

Holocene deposits are also found in the Olbalbal depression which is situated just west of the Crater Highlands. The Olduvai Gorge discharges into the Olbalbal depression and alluvial deposits have been carried via the Gorge's river bed into the depression already from the time when the Ndutu Beds were deposited.

A special form of Holocene sediments are the dunes.

In the area between the Olduvai Gorge and the Gol Mountains the dunes have the shape of true barchans; on the geological map this area is indicated by the name "shifting sands". These black dunes are still active and annual rates of movements - from the east towards the west - of 15 to 20 metres have been recorded (Hay, 1976). During the years they have left long trails, up to 10 km long. The active dunes seem to have originated from wind worked Namorod ash; heavy minerals contents are high, up to 90%! Further to the west, near the National Parks boundary as well as inside the National Park, the dunes have become stabilized by grass vegetation and are considerably finer textures; they are likely to consist for the greater part of wind worked tuffs of older age.

Other Holocene deposits within the study area are:

- Alluvium of the Lake Ndutu basin, which is situated in the western part of the Olduvai Gorge: lake deposits, alluvial fan deposits, colluvial deposits from the surrounding walls of the gorge; all deposits consists mainly of water-reworked volcanic material.
- Alluvium of deeply incised valleys, e.g. the Olduvai Gorge west of the Olduvai crossing, the Mbalageti valley, the Magungu River and its tributaries, the Esoit Ndiakarta River, the Ngare Nanyuki River and the Seronera River. The alluvial deposits consist of coarse textured mixtures of reworked ash and materials from the Pre-Cambrian basement rock - frequently exposed along the valley walls and bottoms - in various ratios. In most of the other valley bottoms and drainage lines within the boundaries of the Serengeti Plain the soils consist of reworked soil material (volcanic ash) from the flanks of the adjacent ridges or hills; residual materials

from the basement rock are relatively rare or even lacking. These mostly fine-textured soils differ strikingly - also in morphological and physical-chemical respects - from the alluvium of the deeply incised valleys and should therefore be separated from the latter.

- Alluvial Plain: a small area in the northern part of the Serengeti Plain near the Ngare Nanyuki airstrip; the area is marked by a pure stand of *Acacia xanthophloea* woodland (Ngare Nanyuki "Groundwater Forest"). The alluvium - mainly reworked volcanic ash - has been deposited by the Magungu River which ends - or rather disappears - in the forest and seems to emerge again as Ngare Nanyuki River about 2 km to the north-west.

The way the Serengeti Plain has been built up can be summarized as follows: The original structure of the Plain was an old dissected surface consisting of Pre-Cambrian basement rocks. During the Pleistocene and Holocene the landscape was covered by eolian deposits of ashes and tuffs up to 100 m thick, that had been ejected during successive eruptions of several volcanoes in the adjacent Crater Highlands. The succession of the ash and tuff deposits show up in the so-called Olduvai Sequence, in which the Beds I (oldest) to VI (youngest) have been distinguished. The deposits of the upper part of Bed V (Upper Ndutu and Naisiusiu Beds) and of Bed VI (Namorod ash) date from the last 60.000 years; they have originated from the still active volcano Oldoinyo Lengai. The ash deposits had probably a strong leveling effect on the topography of the Serengeti Plain, which varies between gently undulating and nearly flat.

4.2. Development of soils within the study area in relation with parent materials.

Two major groups of soils can be distinguished:

1. Soils that have developed from volcanic ash; these soils occupy the greater part of the study area and are covered by treeless (in most places) grassland: Serengeti Plain.
2. Soils that have for the greater part derived from Pre-Cambrian basement rock or materials; they support a so-called "woodland" vegetation (see Part III: Vegetation and soils).

ad 1. Soils that have largely or entirely derived from volcanic ash deposits (soils of the Sediment Plain):
The special nature of the parent material - i.e. alkaline volcanic ash - constitutes an essential factor in the process of soil formation on the Serengeti Plain. The dark grayish brown soils of the Plain (high amounts of dark coloured heavy minerals!) could be expected to have physico-chemical properties that are related with the presence of amorphous materials (e.g. allophanes) such as low bulk densities, high water holding capacity, thixotropy, high cation exchange capacity.
Because of the alkaline character of the ash and in view of the semi-arid climate that prevails in the area, saline or alkali soils are likely to occur, especially in the dryer eastern part of the Plain. On the basis of the geological history of the ash deposits one may expect local differences in soil properties:

- Decrease of the size of the ash particles from the east towards the (north-)west during the deposition of the ash: the further from the source (Oldoinyo Lengai), the finer the particle size and the texture of the parent material.

- Local variations in mineralogical composition of the ash due to deposition during different eruptive phases or to a different origin (different source!). Besides the possible differences in mineralogical composition at the time of deposition, also the factor time will be relevant with respect to soil formation.
- Rejuvenation of the soils. This aspect will be especially relevant for the soils in the eastern part of the Plain (Short grasslands): shortest distance from the source (Oldoinyo Lengai).
  Also during minor eruptions some material may be deposited. Of special importance in this respect is the presence of sodium carbonate in the recent ash deposits of Oldoinyo Lengai which will have had a strong influence on the chemical status of the soils covered by these deposits.
  Hay (1976) gives information on mineralogical composition of the various ash deposits; they may be useful in establishing the age of the soils which fact could reveal the effect of the factor time on soil formation.

In areas within the Sediment Plain that are rich in granitic or gneissic inselbergs (kopjes), e.g. the Moru and Girtasho areas, weathering products of the granite or gneiss will be found throughout the profiles. On the soil surface these weathering products will be washed out by rain. This phenomenon is often called "sandwash". The "sandwash" is especially found at bare spots or at spot with a sparse vegetation cover.

<u>ad 2</u>. - Soils that have for the greater part derived from granitic or gneissic basement rock ("residual" soils): they are found in the Dissected Plain which bounds the Serengeti Plain to the north. They have (very) dark grayish brown (ridges) to very dark gray or black (valleys and depressions) colours; admixtures of a

volcanic ash give darker colours and have had strong effects on physico-chemical properties of the soils. A typical characteristic of these soils is the presence of large amounts of very fine reddish quartz gravel ("sandwash") from the decomposed basement rock in the profiles and on the surface.

- Soils derived from quartzitic basement rock (Nyanzian, Bukoban): These soils are found on and between the hills that bound the Serengeti Plain to the west and north-west. Generally they have (dark) reddish brown colours; admixtures of volcanic ash will have effects similar to those mentioned for the soils derived from granitic or gneissic material. In depressions and on lower slopes also very dark grayish brown and black soils ("black cotton soils") occur.

Both for the granitic and quartzitic soils, soil texture and structure development in a soil profile depend strongly on the position of the profile in a topographic sequence (catena). Their mineralogical composition can be expected to differ strongly from that of the soils of the Sediment Plain.

Part II: Soils of the Serengeti Plain and their characteristics

1. The soil map

The soil map covers an area of roughly 4 800 km^2. This area - often referred to as study area - is located between latitudes 2° 18^1 and 3° 03^1 south and between longitudes 34° 40^1 and 35° 18^1 east.

Paragraph 1.1. discusses the levels of differentiation distinguished for the soil that are found within thestudy area and the criteria that have been used.

Paragraph 1.2. gives some information about the procedures followed in the compilation of the soil map.

In paragraph 1.3. some comments are made on the plotting of soil boundaries.

The soil map and legend have been given as Appendix at the back of the book.

1.1. Discussion on the various levels of differentiation of the soils and the criteria which have been used

A. Highest level of differentiation: Broad Soil Landscapes

Based on the geology and geomorphology 3 Broad Soil Landscapes and a number of Miscellaneous Landtypes have been distinguished:

I. Sediment Plain (Serengeti Plain): It forms the larger part of the study area. Soils have largely developed from wind blown volcanic ashes, overlaying Pre-Cambrian basement rock; the plain has a flat to gently undulating topography and is covered by various types of treeless grassland.

II. Dissected Plain: It bounds the Sediment Plain to the north. Soils have largely developed from residual materials of Pre-Cambrian origin (mainly granitic or gneissic); the soils, however, have been more strongly (in the east) or less strongly (in the west) influenced by volcanic ash deposits; the topography is gently undulating or undulating as a result of dissection; the area is covered by woodland (i.e. wooded grassland or savannah) and grassland.

III. Uplands: This broad Soil Landscape is found to the west of the Sediment Plain. Soils have developed from residual materials of Pre-Cambrian origin (mainly quartzitic) and have been influenced by ash falls locally, especially in the zone adjacent to the Sediment Plain (I); the topography ranges from strongly sloping (hills) to level (backswamps); woodland, very open woodland and grassland form the vegetation types within the area studied.

IV. Miscellaneous Landtypes: Soils have developed from a wide range of parent materials or parent rock; they are found scattered throughout the study area and form striking features in the landscape, although they occupy only small areas.

The Broad Soil Landscapes form broad natural units within the Serengeti ecosystem, and have already been described by Gerresheim (1974) respectively as Landregions 14, 11 and 13; some smaller areas in the north-west (near Banagi) and in the south-east (Simiyu Area) have been included respectively in Landregions 10 and 17.

Studies on the climate (in particular on rainfall) of the Serengeti ecosystem (Norton-Griffiths et al., 1975) showed that also with respect to climate conditions the Serengeti Plain differed significantly from the surrounding landscapes by a more pronounced aridity.

The combined effects on soil formation of the factors parent material, vegetation and rainfall - which differ considerably from those in the surrounding landscapes - have made the Serengeti Plain an unique soil landscape within the entire ecosystem.

B. Second level of differentiation: Soil Landscapes

Because this study is primarily centred on the soils of the Sediment Plain (Serengeti Plain) and soil/vegetation relationships within this area, the following criteria for differentiation of this broad soil landscape have been used:

1. Soil texture and mineralogy (namely the percentages volcanic ash or residual materials present) of the parent material.
2. Degree of profile development (horizon differentiation).

In this way the Sediment Plain (Serengeti Plain) could be divided into 3 soil landscapes: I.1 , I.2 and I.3.

These soil landscapes coincided largely with the three most important grassland zones, respectively: the Short grasslands, the Intermediate or *Andropogon greenwayi* grasslands and the Long grasslands.

Broad soil landscape II was subdivided into II.1 and II.2 , largely on the basis of the amounts of volcanic ash.

The Uplands (III) and Miscellaneous Landtypes (IV) have been differentiated on physiographical criteria using aerial photographs.

No further differentiation, e.g. based on parent material or on horizon differentiation, has been made since this would be beyond the scope of this study.

C. Third level of differentiation: Broad Soil Units.

The differentiation into broad soil units, made for Soil Landscapes I (Sediment Plain) and II (Dissected Plain), has been based on topographic sequences, comparable with the catena concept according to G. Milne (1935):

1. Ridge tops and the flat of gently undulating plain.
2. Flanks (sometimes split into upper and lower flanks in the discussions)
3. Valley bottoms and riverbeds.

Generally, the above units reflected relative differences in texture or structure and physical-chemical characteristics found within each soil landscape fairly well; most of them could be outlined easily on the aerial photographs, because they coincided with distinct vegetation patterns in many parts of the grassland plain.

D. Fourth level of differentiation: Soil Units

On this level attention has been paid to one special physical-chemical feature: the occurrence of a petrocalcic horizon in the soil profile — i.e. within the upper 120 cm (depth within reach of the Edelman-type soil auger); deeper soil layers have only been studied in soil pits but their characteristics have not been used for the differentiation of soil units — and the depth at which it was found. The reasons for this were the following:

a. Soils with a petrocalcic horizon occupied an important part of the study area and especially occurred within soil landscape I.1 which is covered by the Short grasslands ; smaller areas were found in soil landscapes I.1 , I.3 and II.1.

b. Petrocalcic horizons were usually found in soils that were strongly or very strongly alkaline and often internally saline as well; these conditions were thought to have strong effects on plant growth, namely with respect to root development and water availability, especially in case the petrocalcic horizon occurred at shallow depth.

Besides the petrocalcic horizon, there were several other soil factors that had comparable effects on plant growth such as salinity and dense soil structures like a natric horizon, which were found in many parts of the other soil landscapes of the Sediment Plain and the Dissected Plain. The areas affected by these factors, however, were relatively small and often alternated with areas or spots that were less strongly affected or unaffected.

Although these intricate patterns have not been mapped, much attention has been paid to their origin.

1.2. Compilation of the soil map of the Serengeti Plain and adjacent woodlands (scale 1 : 125 000)

Preliminary maps (working sheets) were made at the Serengeti Research Institute, based on uncontrolled mosaics (sheets 25 IV; 37 II, IV; 38 I, III) which had a scale of approximately 1 : 50 000; the mosaics had been compiled from 1 : 30 000 photographs (1953, 1958).

Photointerpretation for mapping was done both on the 1953 and 1958 photopgraphs and on recent "Finn-Map" photographs (1972), approximate scale 1 : 70 000. Because the compilation of a final map from the 1 : 50 000 mosaics encountered considerable difficulties, an uncontrolled mosaic (lay-out) has been composed from the Finn-Map photographs, approximate scale 1 : 73 500; on to this map the soil boundaries have been transferred.

The 1 : 73 500 mosaic has been reduced to 1 : 125 000, based on measurements on the 1 : 125 000 geological maps and the 1 : 250 000 Serengeti map, all compiled by Macfarlane. Distances on the latter maps were assumed to correspond with the scales mentioned, a fact which seems not always to be correct.

Considering the procedures followed in compiling the 1 : 125 000 soil map it is fully recognizedthat this map will show considerable errors when compared with future maps.

1.3. The plotting of soil boundaries

The work on the soil map was started at a time when a considerable number of date on physical-chemical and morphological charateristics of the soils and their relationships with vegetational aspects had already been collected a.o. from former grassland productivity plots used by Braun (1973). This knowledge proved to be a great use in mapping the broad soil units of the Serengeti Plain (I) and the Dissected Plain (II), since topographic differences (between ridge tops and valleys) did not show up very well on the recent aerial photographs (1972). Much better contrast between topograph differences did show up on the 1953 and 1958 photographs. Combinations of topographic features and vegetation boundaries were used for the differentiation on the third level (broad soil units) and fourth level (soil units) of soils in nearly flat areas within soil landscapes I.1 and I.2.

Although topographic differences within the Uplands (III) and the Miscellaneous landtypes (IV) stood out clearly, the use of vegetation-boundaries - which were found to coincide with boundaries between physiographic units - proved to be advantageous for the plotting of soil boundaries.

In some places boundaries were vague: north and north-west of the Gol kopjes, the soils of soil landscape I.1 grade gradually into those of soil landscape I.3 , probably as a result of the combination of parent material, topography and climate (weak gradient in rainfall, see Part I, Ch. 3: Climate), a fact already recorded by Anderson & Talbot (1965). In this area the boundary between Short and Long grasslands was vague too, although differences in vegetation patterns between ridges, flanks and valleys were fairly clear.

Soils belonging to soil landscapes I.1 (Short grasslands) or I.3 (Long grasslands) could be distinguished on the basis of:

1. the presence or absence of grass species that were characteristic for each of the areas: Themeda triandra, Aristida adoensis (respectively very common in, and characteristic for the Long grasslands, and Sporobolus marginatus and the sedge Kyllinga nervosa (Short grasslands only)
2. the presence of large termite mounds - probably of Macrothermes subhyalinus (Kreulen, pers.comm.) - which were common within the Long grassland zone, especially on the ridges (conspicuous on the aerial photographs) but that were lacking in the Short grassland zone. For details on this subject, see Part II: Chapters 2.2 and 2.3.

The area, in which soil units, that had been distinguished on the basis of topographic characteristics, could not be fitted in one of both soil landscapes by using the above criteria, has been indicated as transitional zone.

For drawing the boundaries between soil units belonging to soil landscapes I.1 (Short grasslands) and I.2 (Intermediate or *Andropogon greenwayi* grasslands) the following criteria have been used:

1. topography: I.2 had a more flat topography
2. presence or absence of the grass species *Andropogon greenwayi*, whose distribution had been found to be almost exclusively restricted to soil landscape I.2. The presence of *Andropogon greenwayi* showed up clearly on aerial photographs.

The boundaries between soil units of soil landscapes I.2 and I.3 were drawn, based on:

1. topography
2. presence or absence of *Andropogon greenwayi* (I.2 only)
3. presence or absence of large termite mounds (I.3 only).

The stands of *Andropogon greenwayi* and the large termite hills showed up very well on the larger scale aerial photographs (1953, 1958).

Also between soil landscapes I.1 and I.2 and between soil landscapes I.2 and I.3 transitional zones did occur; these areas, however, were much smaller than the zone between soil landscapes I.1 and I.3.

Many of the boundaries between the soil units distinguished within soil landscape I.1 (fourth level of differentiation, indicating the depths of a petrocalcic horizon) should be considered as tentative.

Areas, in which the petrocalcic horizon occurred at shallow depth (e.g. within 30-50 cm) could be located fairly accurately, as these areas showed up on the aerial photographs as lighter coloured spots, due to the higher percentage of bare soil at these sites.

In case the petrocalcic horizon occurred deeper than 30 cm (i.e. in the greater part of the soil landscape I.1), the above did not apply and boundaries between units with petrocalcic horizons at different depths (e.g. I.1.1.2 and I.1.1.3 , I.1.2.1 and I.1.2.2) have been drawn on the basis of topography (aerial photographs) and a limited number of field checks.

2. Description and distribution of the most important soil units within the Serengeti Plain

The descriptions and discussions deal mainly with the soils of broad soil landscapes I (Sediment Plain or Serengeti Plain) and IV (Miscellaneous landtypes).

To the soils of the Dissected Plain and the Uplands (respectively broad soil landscapes II and III) little attention has been paid, partly because of shortage of data (Uplands), partly because both landscapes formed part of the study area of my successor (Tj. Jager), who did a study on the soils of the woodlands.

Broad soil landscape I has been divided into three soil landscapes: I.1 , covered by the so-called Short grasslands, I.2 which supports the Andropogon greenwayi or Intermediate grasslands, and I.3 which coincides with the Long grasslands. The three soil landscapes have also been indicated respectively as the A, B and C regions (Fig. 8).

In the text the names of the main grassland zones are often used as synonyms for the corresponding soil landscapes; occasionally the region notations have been used in the same way.

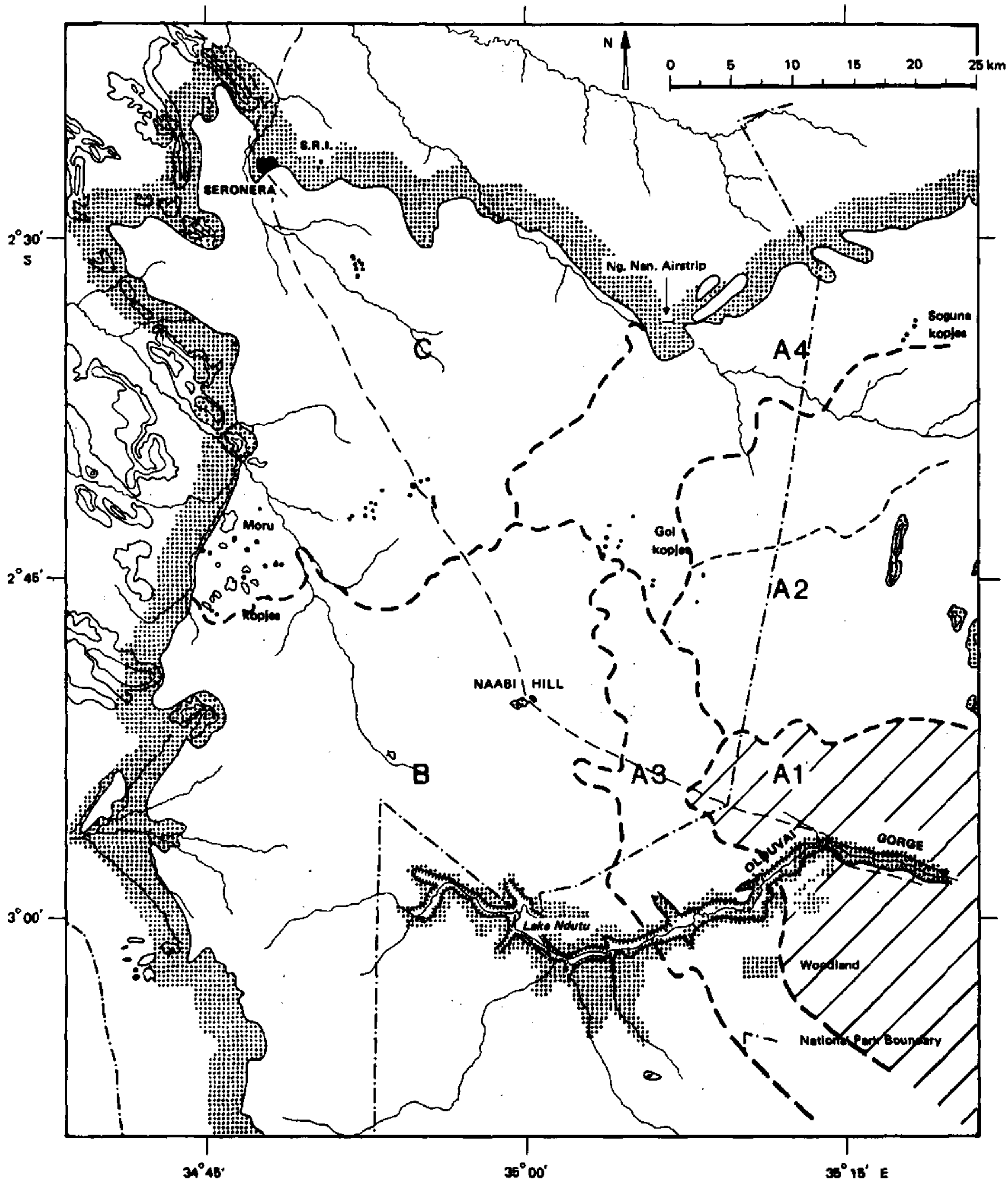
The soils and their properties are discussed on the basis of the catena concept (Milne, 1935).

In view of the gradual change in parent material and annual rainfall from the south-east towards the north-west, and considering their combined effect on the pedogenesis, it was thought that in this way the clearest picture of similarities or differences between the various soil units would be obtained.

2.1. Soils of the Short grasslands (soil landscape I.1 or A-region):

Dark grayish brown loamy and sandy soils with a weak horizon differentiation, predominantly calcareous, with a petrocalcic horizon at some depth in many places, mostly saline or alkaline.

Fig 8: Location of the A.1 area



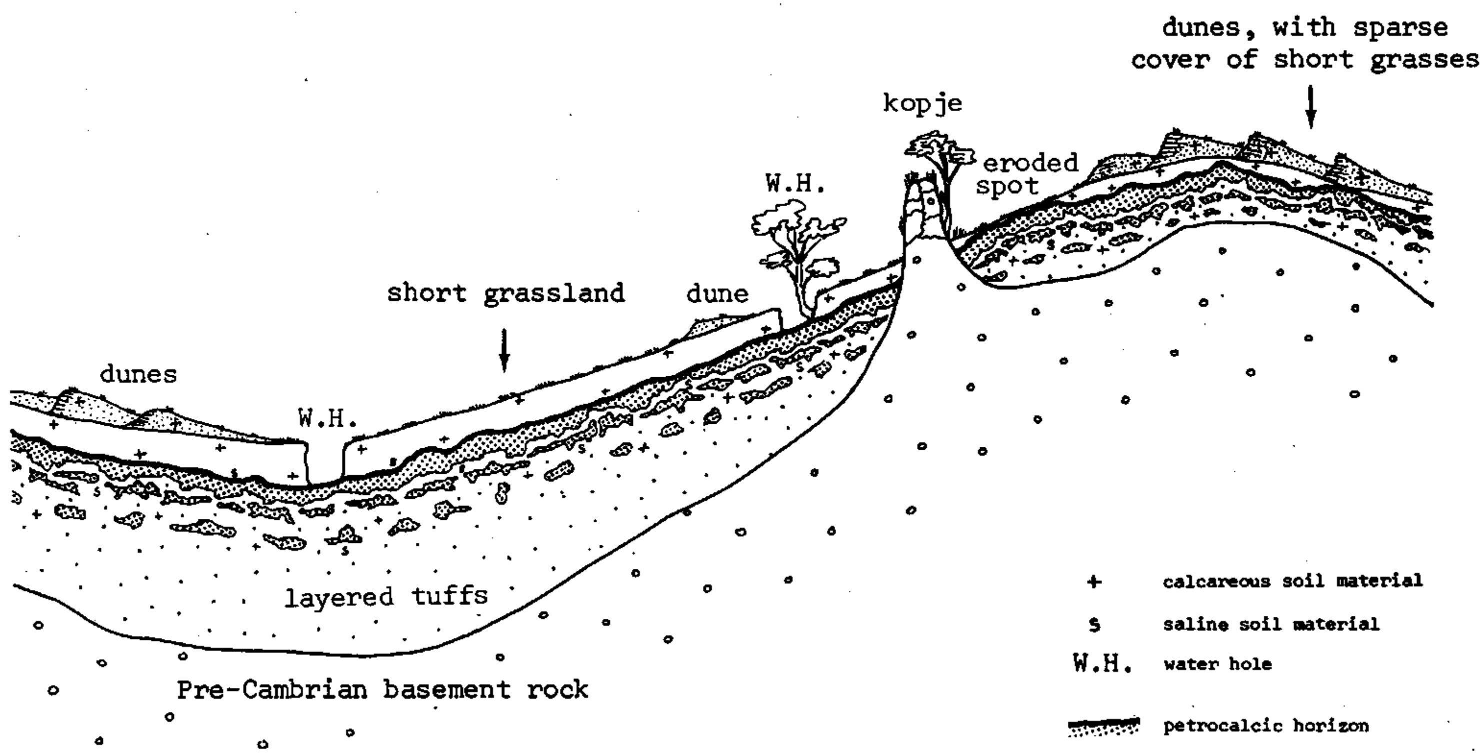
Soil landscape I.1 has been subdivided into 4 areas: A.1 , A.2 (Lemuta area), A.3 (Olduvai area) and A.4 (Sametu-Soguna area).
The locations of the areas distinguished are shown in Fig. 8 .
Preceding the descriptions of each of the four areas - and also of the two remaining regions (B and C) - the map shown in Fig. 8 will be repeated .

2.1.1. Soils of the A.1 area

2.1.1.1. Description of the landscape, topography

The A.1 area is situated in the south-eastern part of the study area. It is divided by the Olduvai Gorge into a northern and a southern part (Fig. 8). The descriptions and discussions that will follow, have largely been based on data and records from the part north of the Gorge.
The topography ranges from nearly level to gently sloping and gently undulating; slopes are long, slope gradients vary between 2 and 5 or 6%. The valleys are broad and flat and drain towards the Olduvai Gorge; some valleys have one distinct drainage line or river bed, others have fish-bone shaped drainage patterns (they show up fairly well on the recent aerial photographs) that run downwards from the broad flanks and converge at the valley bottom (areas north-west and south of the Olduvai crossing, indicated by dotted lines on the soil map). The area is marked by the occurrence of low dunes, for the greater part stabilized by the present vegetation; they occur in both the valleys and on the ridges; they are discussed separately under Miscellaneous land types.
Most common soil units within this area: ridge, flank and valley bottom soils, in which a petrocalcic horizon is found mostly within a depth of 50 cm (resp. I.1.1.1 , I.1.2.1 and I.1.3.1), and dune soils (IV. 7).

Fig. 9 : Soil landscape I.1 (Short grasslands): A.1 area.



The grass cover is characterized by the term "Short grassland", the basal coverage is low (10-20%) especially on the ridgetops and the dunes.

The mean annual rainfall amounts 500 mm or less (see Part I, Ch. 3: Climate).

2.1.1.2. Morphology

The morphological characteristics of the soils within a catena have been outlined schematically in Fig. 9 .

- Soil structure: only weak or moderately weak subangular blocky structures were found in the top 10 or 20 cm, in which the organic matter percentage exceeded 1%; all soil profiles had a surface crust, which was especially well developed at bare spots between the grass clumps. Below the surface the soils are very porous (spongeous porosity).
- Petrocalcic horizon: found in all soils, but at varying depths; attention to the physical-chemical aspects will be paid later on (2.1.2.). The petrocalcic horizon formed a continuous horizon and was impermeable for roots; therefore, the depth at which it occurred, formed the limit for root development and had a strong effect on the water storage and potential water availability.

  On the ridges (I.1.1.1) the petrocalcic horizon was found at depths between 0 and 30 cm; low outcrops occurred abundantly. On the flanks (I.1.2.1) its depth varied between 30 and 60 cm (40-50 cm on the average), in the valleys and valley bottoms (I.1.3.1) between 30 and 75 cm.

  The greater depths, recorded on flanks and in the valleys, were especially found in soils of the fish-bone like drainage lines and in the coarser textured deposits of river beds. The vegetation of these spots was marked by the occurrence of herbs (especially *Solanum incanum*); locally tree regeneration (*A. tortilis*)[1] was found (e.g. just north of the main road and the Olduvai Gorge).

[1] *Acacia tortilis*

2.1.1.3. Physical characteristics

- Texture: field observations did not reveal a strong differentiation between textures of ridge, flank or valley(bottom) soils within a catena; ridge soils tended to have coarser structures. Texture may vary between loamy (very) fine sand (mostly in south eastern parts) and (very) fine sandy loam (western parts). Dune soils (IV.7) and some river beds (IV.2) (e.g. those just north of the main road that are marked by tree lines of *A. tortilis*) had coarse sandy textures. The sand and silt fractions in these soils were found to consist of sand respectively silt-sized aggregates of heavy minerals, amorphous minerals (presumably allophanes) and possibly zeolites, cemented by lime : pseudo sandy character. More details on this phenomenon are found in the discussions on soils of the A.2 area (2.1.2., BARSEK profile).
- Infiltration and water retention: no data were available. In view of data obtained in the A.2 area (BARSEK, SEK-NE)-which will be discussed later on- and the similarity in parent material, soil structure and porosity, the permeability of the surface layer might be estimated as moderate, that of the subsoil moderately rapid or rapid . In general, a more rapid permeability could be expected because of the coarser textures, that are found in this area (judged from field observations). Occasionally standing water has been recorded in the valleys, but this only happened during long lasting and heavy rainstorms.

  The sandy dune soils have a rapid permeability.

2.1.1.4. Chemical characteristics

Data are very much incomplete; a summary is given in Table 4 .

- Alkalinity: the pH values mostly varied between 8.0 and 9.0 within a profile (alkaline soils); differences in alkalinity between profiles at different relief positions were slight. Mostly the pH increased with depth.

Apart from a single exception, the pH of the saturated pastes (pH_p) exceeded that of the saturation extracts (pH_e); this was typical for soils within the A.1 area and also in some parts of the A.2 area.

- Salinity: the few EC_e figures available suggest that the soils are likely to be salt-free (EC_e lower than 4 mmho/cm) down to the petrocalcic horizon at 50 cm. Below this depth salinity may occur as shown by the data from profile 51 in Table 4 (Nae-site near the Park entrance, flat plain); the soil was nearly saltfree down to 50 cm at which depth the petrocalcic was usually found, but strongly saline at lower depth e.g. in places where depression-like discontinuities of the petrocalcic horizon occurred ("pockets"); salinity has also been recorded (by taste) just below the petrocalcic horizon at depths of 40-50 cm.
- Salt composition: in the topsoil Ca^{2+} + Mg^{2+} were dominant, while the amounts of K^+ and Na^+ were equal; downwards, at increasing pH values, Na^+ became the dominant cation. For most samples there was a marked and unexpected discrepancy between the value (10 x EC_e in mmho/cm) and the sum of cations in solution (meq/l), the latter exceeding the total of meq/l based on 10 x EC_e (see Richards et al., 1954) considerably. The reason for this is likely to be the following: nearly all extracts from the saturated pastes were turbid, due to the presence of very fine lime and soil particles (largely consisting of amorphous materials) that had passed through the filter during the extraction procedure (suction). During the determination of soluble Ca^{2+} + Mg^{2+} (by titration with versenate) also exchangeable Ca^{2+} + Mg^{2+} and Ca^{2+} from the lime have probably been titrated. This interference was indicated by the very gradual and slow colour change near the endpoint of the titration, especially when a low titration rate was applied.
- Lime: Throughout the region free $CaCO_3$ has been recorded to occur up to the surface; differences in lime contents and distribution patterns in

Table 4 : soil landscape I.1, A.1 area (Short grasslands): chemical data

profile depth (cm)	SP	pH_p	pH_e	EC_e	Na^+	K^+	$Ca+Mg^{2+}$	Sum +	$CO_3^{2-}+HCO_3^-$	Cl^-	SO_4^{2-}	NO_3^-	Sum -	% Lime
					all in meq/l (saturation extract)									
29. (Valley bottom, flat) 2.5 km W of Olduvai crossing														
0-10	40.5	8.20	8.03	0.44	0.87	0.77	3.74	5.38						3.91
10-20	42.8	8.29	8.00	0.63	1.33	1.38	4.69	7.40						5.61
20-30	42.2	8.46	8.30	0.45	4.04	0.98	3.71	8.73						7.18
30-40	39.6	8.61	8.52	0.66	6.00	1.63	5.06	12.69						8.13
40-50	35.4	9.10	9.09	1.80	16.74	1.84	3.71	22.29						8.36
30. (Riverbed, sandy) 2.5 km NW of Olduvai crossing														
0-20	47.2	7.90	7.94	1.53	1.35	1.57	12.69	15.61						4.41
20-40	42.4	8.34	8.16	0.42	0.87	0.63	4.22	5.72						6.34
40-55	37.2	8.47	8.27	0.40	1.06	0.52	5.13	6.71						7.42
55-70	32.9	8.35	8.27	0.42	1.57	0.46	4.05	6.08						5.88
51. Nae (flat plain, near Park entrance)														
0-10	47.4	8.11	8.17	0.77	1.28	1.18	6.53	8.99	6.96	0.60	0.94	-	8.50	1.41
10-20	51.1	8.24	8.19	0.56	1.25	1.03	2.93	5.21	5.92	0.32		-		4.65
20-30	51.4	8.37	8.34	0.53	2.26	0.99	3.67	6.92	6.20	0.34	0.56	-	7.10	6.62
30-40	47.0	8.52	8.52	1.40	11.30	1.45	2.47	15.22	6.89	1.14		-		7.97
40-50	43.9	8.76	8.73	7.00	67.83	3.91	3.80	75.54	9.64	35.94	27.00	-	72.58	8.74
50-60	39.7	9.23	9.22	9.00	91.74	4.07	1.63	97.44	19.11	40.97		-		9.32
60-80	37.5	10.25	10.24	20.40	259.13	8.44	- 1)	267.57	142.05	51.34	58.88	-	252.27	8.52

1) extracts too dark

the soils between profiles at various relief positions within a catena were not significant except for the dune soil (App. 2); in the other profiles a zone of maximum accumulation occurred at some height above the petrocalcic horizon (Table 4 and App. 2).

Remarks on the biological activity have been made at the end of Chapter 2. The classification of the soils - according to Soil Taxonomy (1975) - has been dealt with in Chapter 4.

2.1.2. Soils of the A.2 area (Lemuta area)

The A.2 area is found north of the A.1 area, extending from the Gol Mountains westwards as far as the Gol kopjes and northwards as far as the Soguna kopjes (Fig. 10).

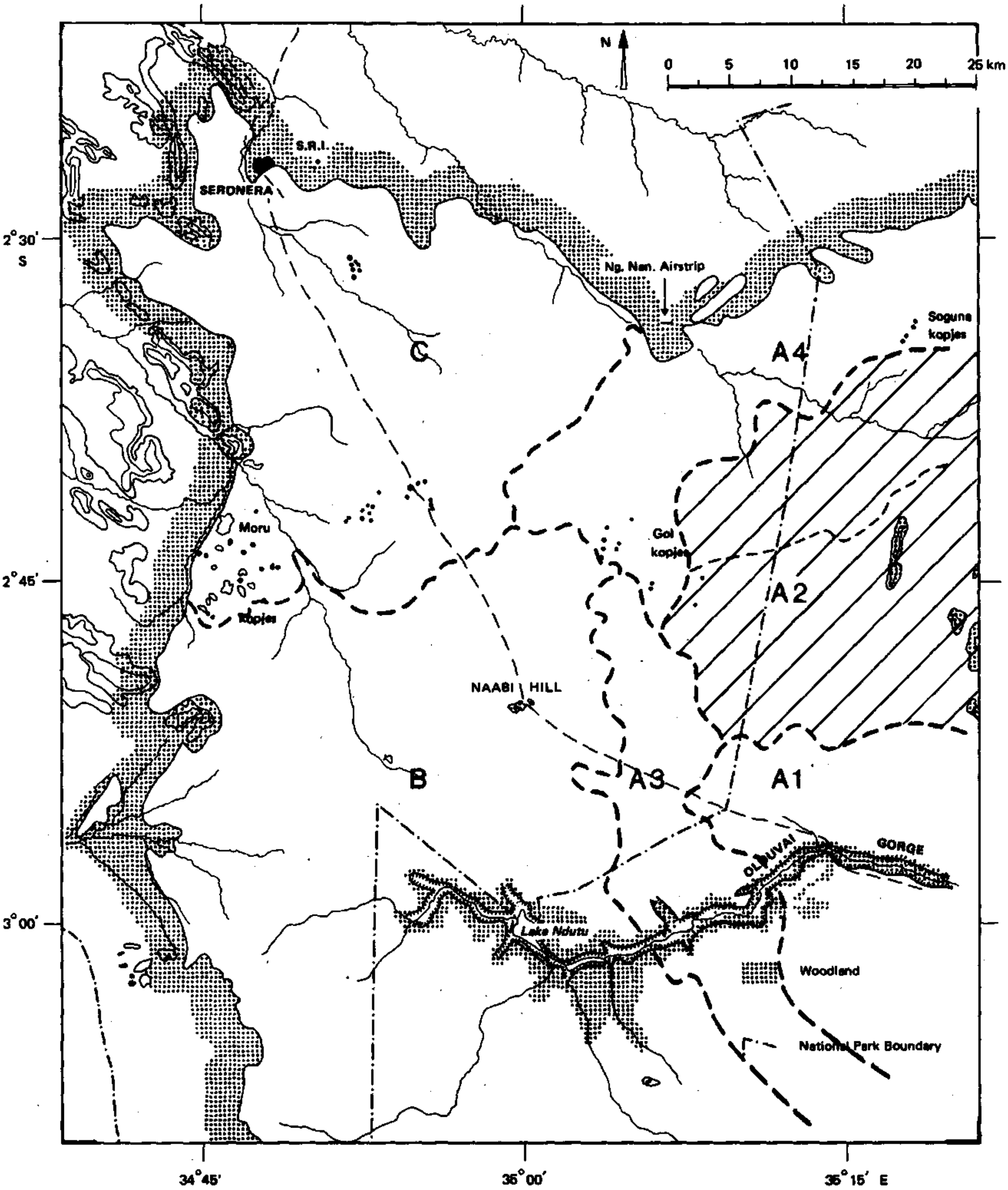
2.1.2.1. Description of the landscape, topography

The A.2 area may be divided into two parts: part one south of the line through Gol kopjes and Lemuta Hill and part two north of it - comparable with landsystem associations 14.2.1 and 14.2.3 according to Gerresheim (1974).

The northern part has a nearly flat topography; slopes are very long (up to several kilometers) and have gradients of 1 to 2%. The northern area forms part of the main watershed between Lake Victoria and the drainless system of the Olbalbal depression and Lake Natron.

The southern part has a gently undulating topography because the area has been more strongly dissected; the slopes have stronger gradients (2-5%) and are shorter. Apart from the general topography several deeply incised valleys are found: the valleys of the Magungu River and its tributaries, and the short valley 2 km north-east of the Maerua kopjes, just outside the Park boundary (see soil map). Along the steep valley walls petrocalcic horizons of different age form outcrops. In several places the Pre-Cambrium basement

Fig 10: Location of the A.2 area



rock protrudes through the ash deposits; they form small Inselbergs, usually called "kopjes". They are found on the very top of the ridges (South-east kopjes, Barafu kopjes, Soguna kopjes) but also on the flanks and at valley bottoms (e.g. south-west of Lemuta Hill). Nearly all kopjes consist of Sametu gneisses of the Serengeti Group; the two so-called Maerua kopjes consist of well-crystallized ultrabasic rock.

Within the area many "waterholes" are found on ridges, upper flanks and also in the valleys.

The vegetation cover in the Lemuta area represents the typical Short grassland ; only in some valleys and along the walls of deeply incised valleys a different grassland type - often rich in herbs - was found (see Part III: Vegetation and soils).

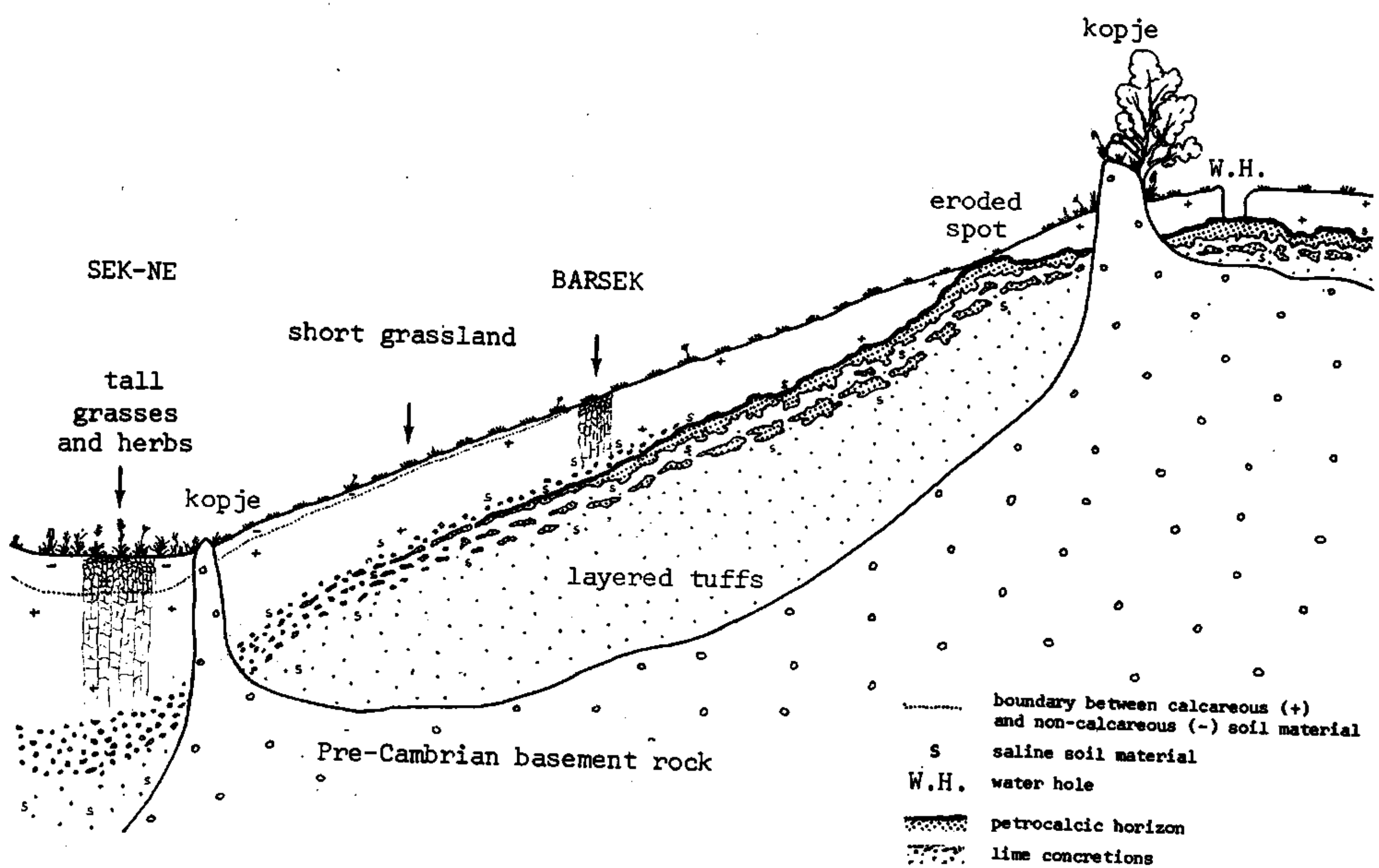
On flanks in the southern part of the area, especially outside the Park boundary, a hummocky microrelief was found in many places; the low hummocks were covered by short grasses, the overall coverage was low. The hummock's origin is probably due to erosion processes.

The mean annual rainfall ranged from 450 mm in the east to 550 mm in the west. The most important soil units are: Loamy soils of the gently undulating plain and ridges with a petrocalcic horizon within 50 cm, deeper than 50 cm, or deeper than 50 cm or without a petrocalcic horizon (respectively I.1.1.1 , I.1.1.2 or I.1.1.3); loamy soils of the flanks with a petrocalcic horizon deeper than 50 cm (I.1.2.2); loamy and sandy soils of the valley bottoms with a petrocalcic horizon deeper than 50 cm or without a petrocalcic horizon (I.1.3.2).

2.1.2.2. Morphology

Fig.11 shows an example of a catena in which the most important soil units are represented. The catena has been outlined on the basis of data from a transect appr. 2 km north of the South-east kopjes, that runs from the

Fig.//: Soil landscape I.1 (Short grasslands):A.2 area.



south-east towards the north-west (SEK-NE transect). The area includes two standard profiles: SEK-NE (South-east kopjes north-east), located at a valley bottom and forming part of the above transect, and BARSEK (Barafu-South-east kopjes) which coincided with a former grassland productivity plot, used by H.M.H. Braun (1973).

- Soil structure: Detailed descriptions of the profiles BARSEK and SEK-NE are given in Appendices 3 and 4.

  Soil structure appeared to be most strongly developed in the dark coloured top soils (very dark grayish brown),which had the highest organic matter contents. In the BARSEK profile, situated on a flank (long even slope with a gradient of 1-2%), the dark top soil had a thickness of 45 cm and had a moderate (top) to weak (lower depth) medium to coarse subangular blocky structure with many of the elements attached to the roots. In the valley bottom profile (SEK-NE), the dark layer had a thickness of over 1 metre with moderate medium and coarse subangular clods (top) to moderately weak coarse and very coarse blocky or prismatic (below). On bare spots between grass clumps, which form shallow depressions, especially on the flanks, the profile is covered by a surface crust, visible on the profile walls as thick or very thick platy elements; they probably did originate by slaking. Below the dark top layer, soil structures were mostly very weak or even absent (structureless, massive or loose) while the colour of the soil material was lighter and yellowish (both higher values and chromas).

- Porosity: Sponge-structure; abundant very fine pores occurred between soil particles and fine aggregates; cracks were narrow and occurred in the top 5-10 cm only, especially in densely rooted parts e.g. below and around grass clumps.

- Petrocalcic horizon:

1. Depth: on the ridges in the southern part of the A.2 area the depth of the petrocalcic horizon varied between 30-50 cm in the east (I.1.1.1) and 50-70 cm in the west and north-west (I.1.1.2); on ridges and in the nearly flat areas in the northern part the petrocalcic horizon was mostly found below 50 cm (I.1.1.2). On the flanks the depth varied between 50 (east) and 100 cm (west and north-west). The depth seemed to be constant over the greater part of the flanks (e.g. 75 cm in the SEK-NE transect and also at BARSEK); depth only increased in the lowest parts (transition to valley bottoms).
   In most parts of the flanks, especially the lower parts, the petrocalcic horizon was covered by a horizon rich in fine and medium sized concretions, consisting of weakly to strongly cemented soil material. In eroded areas along the deeply incised valleys(e.g. Magungu River and tributaries) the petrocalcic horizon is found very close to the soil surface.
   In the valleys the depth usually exceeded 1 metre, and in the SEK-NE profile (broad,flat valley bottom) no petrocalcic horizon was found within 2.70 m; in the latter profile the petrocalcic horizon might even lack completely.
   Outcrops of the petrocalcic horizon were frequently found at eroded spots, especially in the area east of the Park boundary and at the bottom of waterholes.
2. Morphology of the patrocalcic horizon: On top the petrocalcic horizon had a vesicular appearance. The top 1-5 cm had a darker colour and a much greater hardness (only breakable by hammer blows) than the material beneath this layer, which was still strongly cemented; on cross section, wavy to irregular laminar structures could be observed, especially in

the top 1-5 cm. Fine and medium channels and even large vesicular cavities were commonly found inside.

The continuous phase of the petrocalcic horizon had a thickness varying between 5 and 20 cm. The upper boundary was mostly smooth but locally strongly irregular ("pockets"); its lower boundary was mostly irregular. Below the continuous phase coarse and very coarse lumps of cemented soil material were found; in general cementation became less strong with increase of depth; in some places the lumps had grown together, forming banks.

Details on chemical and mineralogical composition of the petrocalcic horizon will be given under physical and chemical characteristics.

2.1.2.3. Physical characteristics

- Texture, mineralogy

Data on soil texture from BARSEK (Table 5 ; samples pre-treated with Na-EDTA - see Part I, Ch. 2: Methods -) and SEK-NE(Table 5 samples treated according to standard procedures for mechanical analysis at Oosterbeek - see Methods) show the silty character of these soils: in the dark coloured topsoil the silt fraction amounted nearly 50%, the sand (largely fine and very fine sand) and the clay fractions each about 25%. In the petrocalcic horizon, the particle size distribution closely resembled that of the overlaying horizons; the clay percentage was even slightly higher. Below the petrocalcic horizon there was a decrease in the clay content and an increase of the sand fractions. Soils of the ridges tended to be more sandy than those of the slopes, valleys and valley bottoms; soils adjacent to the A.1 area had coarser textures irrespective of their relief position.

content was found in the upper part of the petrocalcic horizon. Below the petrocalcic horizon there was a rapid decrease, coinciding with a decrease of the lime content only; below 120 cm no chabazite was found anymore. The percentage amorphous materials, however, appeared to be at the minimum in the petrocalcic horizon, while at lower depth the highest percentage was found (compare with the absence of chabazite). From investigations made on total soil and clay fraction separately (X-ray diffraction and photographs) the amorphous minerals and chabazite appeared to occur in all particle size classes. It was surprising to find that mechanical analysis, carried out according to standard procedures (by which the major part of the amorphous material and zeolites had been dissolved by HCl) gave nearly the same results as the method in which the Na-EDTA treatment was applied; this meant that in the BARSEK profile the amorphous minerals and the chabazite were distributed in equal ratios over the various particle size classes. Moreover,the above results revealed the true nature of an important part of the sand and silt fractions: minute aggregates in which the various minerals have been set in a matrix of $CaCO_3$ and possibly also $Ca.Mg(CO_3)_2$ (petrocalcic horizon!) Some evidence for this did already exist because sand graines of the coarse fractions were recorded to desintegrate into much finer particles under pressure which could be observed during sieving procedures, by which the sand grains ("pseudosand") were rubbed against the sieve gauze by a brush (untreated sample; only water was added). The occurrence and distribution of chabazite throughout the BARSEK profile is probably closely related with soil forming processes under highly alkaline and strongly saline conditions in combination with the presence of $CaCO_3$.

Checks for chabazite, done on samples of the valley bottom profile (SEK-NE), proved to be negative; amorphous clay, however, was found in considerable amounts (diffractograms!). It should be realized that the valley bottom profile probably had developed from deposits of pre-weathered soil material (mainly from surface layers), that had relatively low lime and salt contents and in which the special physical environment, that might have been necessary for the forming of chabazite, could not have existed.

- Bulk density

Data obtained from the BARSEK and SEK-NE profiles have been given in Table 6a.

In the BARSEK profile the dark top soil (0-25 (50) cm) had the lowest values, partially due to high organic matter contents. The highest bulk density was found in the horizon overlaying the petrocalcic horizon; this was probably caused by the numerous concretions included in the ring samples. The lowest value (at 30-35 cm depth) was found in the layer just below the A.1.1 horizon; in the dry season this layer had a very loose and powdery consistence which could be observed frequently during the collection of soil samples by auger. Throughout the SEK-NE profile the bulk densities were less variable (homogeneous profile, few concretions only); the lowest value was close to the limit of 0.85 which has important consequences for the soil classification (see Chapter 4 : Classification).

- Water retention and water availability

Figures 12a and b show the moisture retention or pF-curves for various soil layers in the BARSEK and SEK-NE profiles. The curves resemble the pF characteristics of a loess soil, although the moisture percentages at saturation and field capacity of the latter soils use to be somewhat lower.

Table 6a Soil landscape I.1 (Short grasslands): Bulk densities and soil moisture contents at various moisture tensions in a desiccating soil

A: BARSEK

depth horizon (cm)	depth ring sample (cm)	bulk density (g/cm^3)	moisture contents (Vol %) at:					SP sat.soil paste
			pF≈0	pF1	pF2	pF4.2[1]	pF5.6[1]	
0-12.5	2.5-7.5	1.02	64.0	62.9	57.2	18.6	8.2	55.6
12.5-25	15-20	0.98	66.2	65.1	59.6	18.8	8.3	62.7
25-35	30-35	0.92	70.1	67.6	59.4	17.1	8.0	56.3
35-45	40-45	0.95	70.3	66.7	55.5	16.3	9.0	45.7
45-60	50-55	1.06	63.7	59.6	50.7	20.8	10.4	48.3
60-70	62.5-67.5	1.08	59.6	57.5	50.4	23.1	10.8	51.6
B: SEK-NE								
0- 16	5-10	0.92	-	63.9	56.5	18.9	10.0	63.7
40- 70	50-55	0.89	-	64.6	58.4	17.1	10.1	59.7
70-110	80-85	0.90	-	62.8	56.8	18.3	11.9	51.0
110-170	122.5-127.5	0.86	-	62.7	55.1	17.7	11.3	44.8

[1]) mixed samples; results representative for the total thickness of the soil layer investigated

Table 6b Soil Landscape I.1: Potential wateravailability

moisture tension at field capacity (as per pF)	available moisture (mm)[1]					
	BARSEK			SEK-NE		
	0-40	40-70	0-70	0-40	40-70	0-70
pF 2.0	160	92	252	145	129	274
pF 2.5[2]) (1/3 bar)	118	58	176	95	79	174

[1]) (mm H_2O at field capacity - mm H_2O at permanent wilting point), accumulated for the soil layers distinguished

[2]) moisture contents at pF 2.5 estimated from pF curves

In the BARSEK profile, the curves for the upper horizons (0-40 cm, rich in organic matter) and the horizons overlaying the petrocalcic horizon (40-70 cm, low organic matter contents) were slightly different, resulting in potentially higher amounts of available water in the top soil (see water availability). Within the more homogeneous SEK-NE profile hardly any difference could be found between the various depths. For the same soil layer the moisture percentages of puddled soil pastes at saturation (SP values) were significantly lower than the moisture contents at saturation (converted to weight percentages) of undisturbed samples (see Table 6a), especially when bulk densities of the undisturbed soil material were lower than 1.0. This can be explained by the strong decrease of the porosity - i.e. increase of the bulk density - caused by the disturbance of the natural arrangement of the particles and minute aggregates during puddling.

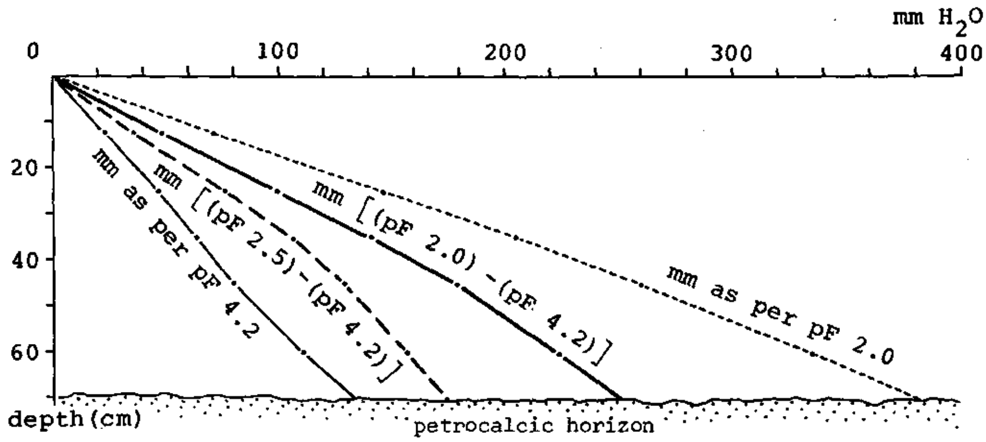
The increase of bulk density could also be observed by digging in these soils: the volume of the soil material dug out appeared to be too small to refill the hole completely.

During the retention experiments however, no changes in volume (no shrinking or swelling) for any of the BARSEK or SEK-NE ring samples occurred. Figures 13a and b give the cumulative amounts of potentially available water for the two standard profiles while in Table 6b the figures for the top 70 cm of both profiles have been compared.

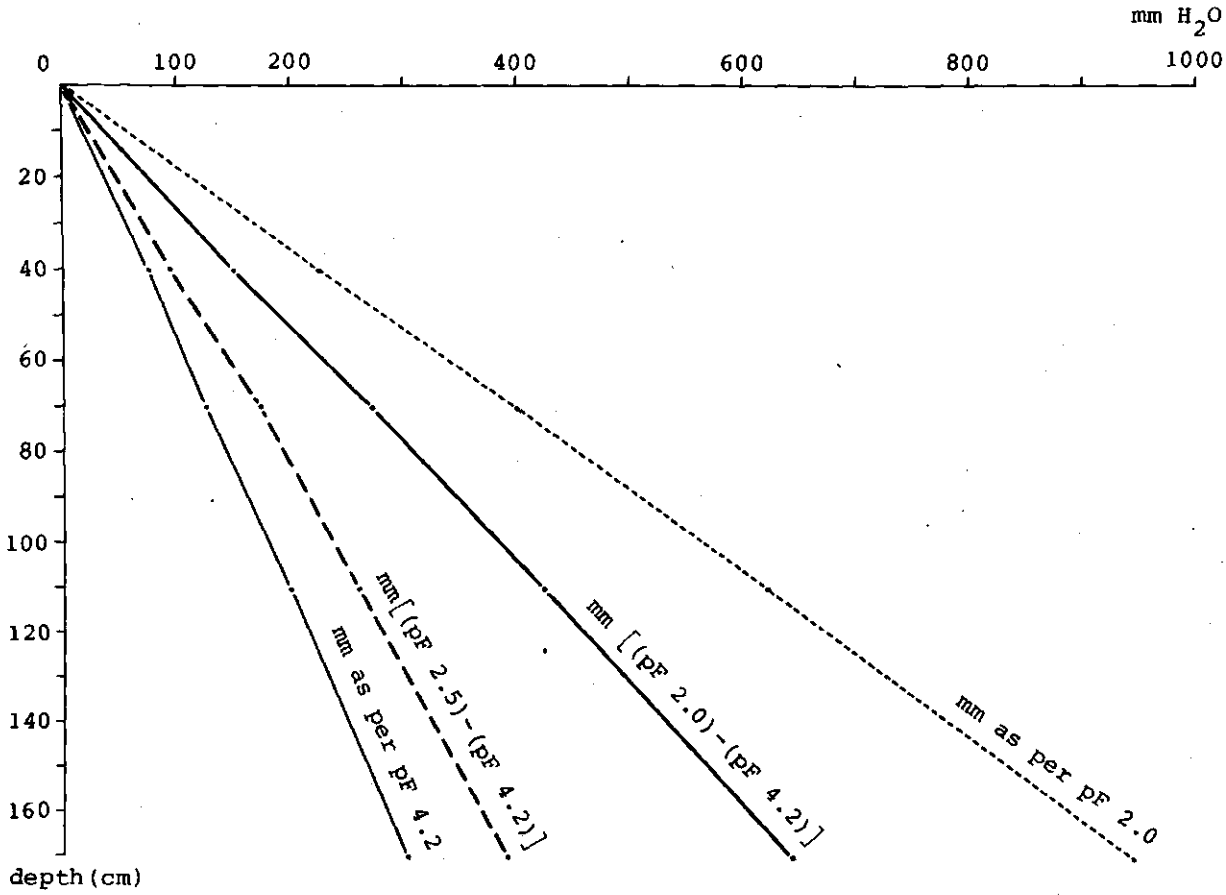
In case the field capacity is estimated to correspond with the moisture content at pF 2.0., the available water amounts roughly 40 mm per 10 cm layer for both BARSEK (0-40 cm) and SEK-NE (0-170 cm).

From moisture determinations on soil samples that had been moistened in the field and from which the excess of water had sagged, the contents at field capacity were found to correspond better with those at a moisture stress of 1/3 bar (pF 2.5); for this reason also the 1/3 bar

Fig.13: Soil landscape I.1 (Short grasslands): Amounts of soil moisture at pF 2.0 and pF 4.2 (mm) and amounts of available moisture (mm) accumulated with depth for 2 characteristic soil profiles.



a: BARSEK (gently undulating plain).



b: SEK-NE (valley bottom).

values have been taken into account (moisture contents at 1/3 bar estimated from the pF-curves): BARSEK: about 30 mm available water per 10 cm between 0 and 40 cm and 20 mm between 40 cm and the petrocalcic horizon; SEK-NE: 23-27 mm per 10 cm throughout the profile.
From the figures and tables the storage capacities and availability trajects appeared to be extremely favourable for both profiles.
Besides the factor soil moisture tension, the availability of water for plant growth depends also on the osmotic value of the soil moisture: osmotic potential. The latter becomes very important in the salt-affected parts of the profile, e.g. for the BARSEK profile below 40 cm.
The osmotic potential may be considered as a relevant factor for most soils within the area discussed, in particular for those of the flanks. Osmotic effects will be, of course, of less influence for salt-tolerant grass species, e.g. Sporobolus marginatus, which is one of the dominant species within the Short grasslands (see Part III: Vegetation and soils).

- Thixotropy

This phenomenon has been defined in Soil Taxonomy (1975) and has been recorded to occur in soils of volcanic origin in which amorphous materials form a dominant fraction of the total soils. The latter is the case for all soils within broad soil landscape I and for many of the soils of Broad Soil Landscapes II and III.
Thixotropy showed up during the preparing of saturated soil pastes: after some water had been added to the dry and loose soil material the soil turned readily to a doughy paste while mixing with a spatula. The paste often had a peculiar, sometimes very strong, plasticity and stickiness, allowing to pull wires from the pasty material. This consistence remained nearly unchanged over a wide moisture traject, but near the saturation point its character changed rapidly: the

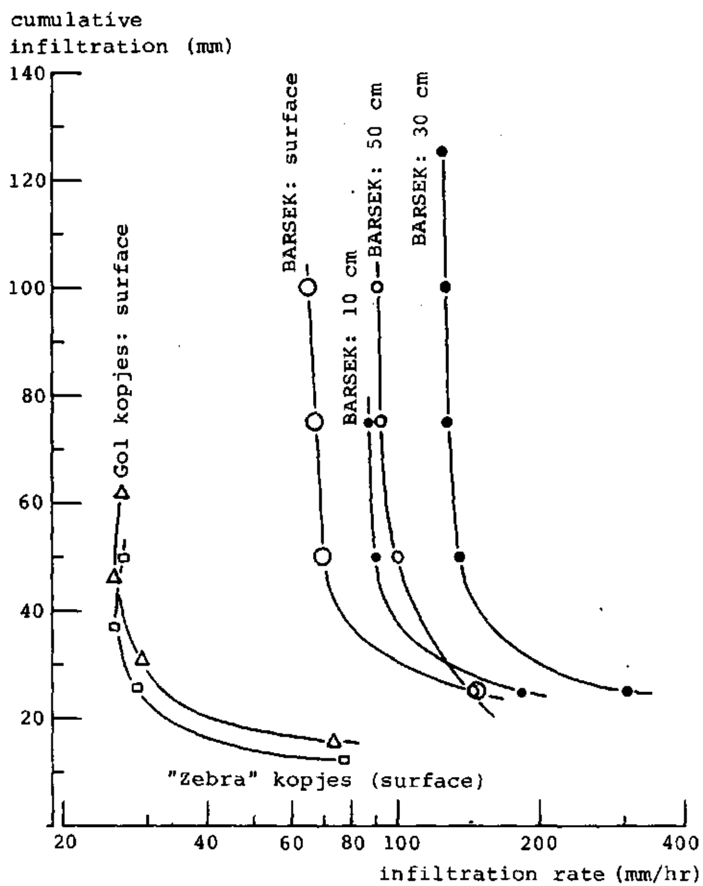
slightest bit of over-saturation — a few ml of water per 100 g of soil - turned the paste into a muddy liquid. After a night standing, the slight excess of water added was standing on the paste's surface and the paste had regained its tough, doughy consistence again; however, after having mixed the standing solution with the paste, it changed immediatly into the muddy phase again. Also in the field evidence of thixotropy could be observed: undisturbed bare walls of erosion steps, waterholes and also soil pits kept their shape for a long time, even during the wet season, but under pressure, e.g. by hand, spade, car tyres or trampling by wild animal the soil material was readily transformed into a smeary substance.

- Infiltration

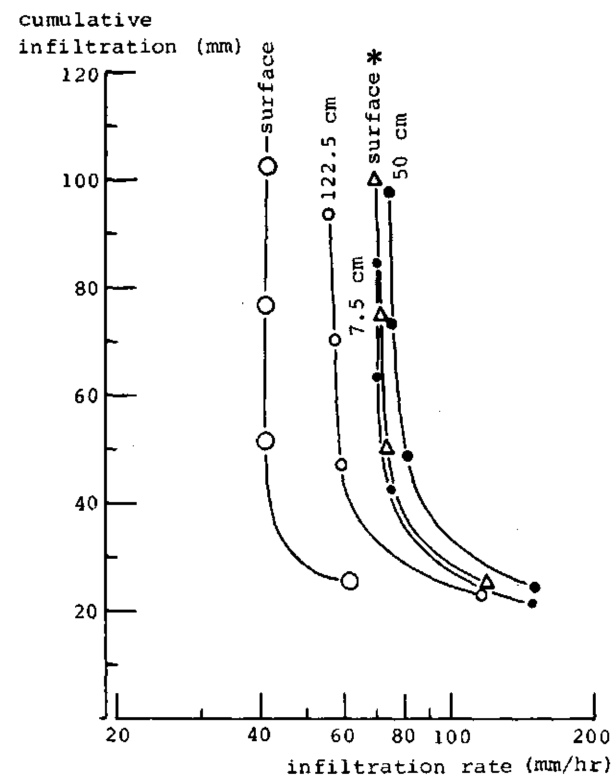
Within the soil landscape I.1 simple infiltration experiments (see Part I, Ch. 2: Methods) have been carried out at four sites at various depths in order to get an idea about permeability for rain water and run-off. Fig.14 and App.5 give a summary of data collected at BARSEK, SEK-NE,"Zebra" kopjes (northern Gol kopjes) and near the Gol kopjes enclosure. The infiltration experiments (rings mostly pressed into the soil by a car jack) have been done in the shallow, bare depressions between the low, hummocky grassclumps, in which rain-water and run-off collect during rainstorms and in which a surface crust had formed as a result of slaking. The BARSEK-data had been obtained only from experiments in which the infiltration rings had been hit into the soil with a hammer. For comparison with other data the latter procedure has also been applied to the surface infiltration at SEK-NE. Infiltration rates appeared to be about two times higher for both the dry and the saturated soil if the rings had been hammered into the soil, which was probably due to cracking of the surface crust. According to the classification in the Soil Survey Manual (1951) the infiltration in the dry surface layer was

Fig.14: Soil landscape I.1 (Short grasslands): Mean infiltration rates as related to total amounts of millimetres water infiltrated in 2 characteristic profiles, measured at various depths, and for the surface layers at two other sites.

Infiltration rings hit into the soil by hammer (BARSEK, SEK-NE surface) or pushed into the soil by car jack (SEK-NE, "Zebra" kopjes, Gol kopjes).



a: - BARSEK (gently undulating plain), rings hit into the soil by hammer.
- "Zebra" kopjes (upper flank), *surface* soil only.
- Gol kopjes (flat plain, near Gol enclosure), surface soil only.



b: SEK-NE: (valley bottom), rings pushed into the soil by using a car jack.

* = rings hit into the soil

moderate to moderately rapid when dry, moderate when saturated. The infiltration rates for air-dry soils were found to exceed the ones in a saturated soil by a factor 1.5 (BARSEK, SEK-NE) to 3.0 (Zebra kopjes, Gol kopjes exclosure, surface layers).

Below the surface there was a marked increase in the infiltration rates: 2 times at a depth of 50 cm in the SEK-NE profile and even 3 times at a depth of about 35 cm in the BARSEK profile (N.B. in the layer with the lowest bulk density!), in comparison with the figures for the surface infiltration. The data in App. 5 show that the infiltration rates for the saturated soils became constant after the first measurement (I) in the dry soil. This reveals the stable configuration of the solid phase (spongeous structure!) of these soils. The figures also show that the crusty surface layer may form a limiting factor in absorbing precipitation and run-off under exceptionnally high rainfall intensities.

2.1.2.4. Chemical characteristics

- Alkalinity and salinity

Most of the soils discussed were alkaline to very strongly alkaline. The pH values in the top 40-50 cm varied mostly between 8.0 and 9.0; in the deeper layers - except for those in the valley bottom profiles - the pH increased rapidly to values between 10.0 and 10.5. In the soil layers that were moderately alkaline to strongly alkaline (traject between pH 7.9 and 9.0 - Soil Survey Manual),the EC_e values seldom exceeded 4 mmhos/cm and were usually lower than 1 mmho/cm. Very strong alkalinity invariably coincided with EC_e values of over 4 mmhos/cm; pH values of over 10.0 were mostly found in strongly saline soils (ECe > 15 mmhos/cm). The high and extremely high alkalinity at lower depth was caused by the presence and accumulation of free $NaHCO_3$ or Na_2CO_3. The carbonates and bicarbonates in the soil owe their presence to recent volcanic eruptions, which were of a strongly alkaline character, and which may even have contained free $NaHCO_3$ and Na_2CO_3 as both salts were found in the crater of Oldoinyo Lengai after eruption; $NaHCO_3$ was recorded to sublimate on the craterfloor (Dawson, 1962). The presence of HCO_3^- and CO_3^- in a profile could easily be detected by tasting.

- Salinity patterns throughout a catena

a. Soils of the ridges: mostly non-saline down to the hardpan; alkalinity increased from the surface downwards from moderately to strongly alkaline. Composition of free salts: in the top 10-20 cm, Ca^{2+} + Mg^{2+} and HCO_3^- were dominant; downwards there was a replacement of Ca^{2+} and Mg^{2+} by Na^+, causing an increase of the pH; CO_3^{2-} started to occur above the petrocalcic horizon. Soil material below the petrocalcic horizon was probably moderately to strongly saline and very strongly alkaline.

b. Soils of the flanks: with respect to alkalinity, salinity and salt composition, the top 30-40 cm of the flank soils closely resembled the top soils of the ridges. At a depth of about 40-50 cm salinity increased rapidly from slightly to moderately or even strongly saline; at a depth between 80 and 120 cm there was a zone of maximum accumulation in which EC_e values up to 35 mmhos/cm have been recorded (Soguna, SEK-WE - see Appendix 6 -); further downwards the salinity tended to decrease. The salt composition changed as well, especially on the anion side: at the increase of salinity around the depth of 50 cm, chlorides and sulphates together with Na^+ were dominant in a layer of 10-20 cm thickness; further downwards there was a very strong increase of CO_3^{2-} and HCO_3^-, equalling or exceeding the total amounts of Cl^- and SO_4^{2-}; Na^+ remained the dominant cation throughout the profile.

c. Soils of the valley bottoms and drainage lines: at SEK-NE the soil was salt-free and only weakly to moderately alkaline till a depth of 1.70 m; moderately saline below 1.90 m; the increase was gradual.

Dominant anions: HCO_3^- in the salt-free part of the profile; in the salt-affected parts Cl^- and to a lesser extent SO_4^{2-}, with HCO_3^- becoming negligibly low. In the salt-free upper 30 cm Ca^{2+} and Mg^{2+} were the dominant cations, below 110 cm Na^+ increased rapidly accompanied by an increase of the EC_e; due to the low pH, Ca^{2+} and Mg^{2+} concentrations stayed relatively high in comparison with the former profiles.

The following summary may be given:

1. In all profiles there was an increase of salinity (accumulation) with an increase of depth, the topsoils were mostly salt-free: internal salinization. Locally some isolated spots marked by external salinization have been recordered.
2. Except for some profiles situated in valley bottoms, EC_e values over 8 mmhos/cm coincided with very strong alkalinity (pH $>$ 9) due to the presence of free Na_2CO_3 (and $NaHCO_3$).
3. The thickness of the salt-free top soil increased in the lowest parts of the flank and especially in the valley bottoms; probably as a results of a more intensive leaching.
4. The maximum concentration of salts accumulated in the subsoil was found on the flanks.
5. With respect to the salt composition there was a tendency to dominance of chlorides and sulphates over carbonates and bicarbonates in the valley bottoms; on the flanks (Cl^- + SO_4^{2-}) were generally equal to (CO_3^{2-} + HCO_3^-) whilst on the ridges HCO_3^- (+ CO_3^{2-}) ions were the dominant anions (Ca^{2+} and Mg^{2+}) were dominant cations in the top 10-20 cm only; at lower depth Na^+ was always the far dominant cation.

pH-values measured on the saturated pastes (pH_p) were sometimes found to be equal or even higher (up to 0.3 pH-value) than the values found in the saturation extracts (pH_e), especially in the range between pH 8.0 and pH 9.0; generally, this applied to both the ridge and the flank soils, but not to the valley bottom soils. Further to the west (BARSEK-west, see Appendix 7[1]) this was not the case anymore. It should be recalled that in the soils of the A.1 area the pH_p consistently exceeded the pH_e.

In the salt affected part of the profiles the soil material was found to stay moist even during long periods of drought whereas no groundwater table could be observed.

Chemical data of the standard profiles BARSEK I, II, III (upper flank soils) and SEK-NE (valley bottom) are given in Tables 7 and 8; the salt distribution throughout the first and the last profile is shown graphically in Fig. 15a,b. Data for some other profiles - situated in various relief positions - are found in Appendices 7[1] and 8[1].

- <u>Lime</u>

All soils, except for some of the valley bottoms, were calcareous up to the surface (lime content $\geqslant$ 1%), although the contents in the top 10-20 cm were on the average lower than in the A.1, area. For data see Tables 7 and 8 and Appendices 6, 7[1] and 8[1]. In most profiles there was a marked accumulation of secundary lime at some depth; in the profiles of ridges and flanks often in the form of hard concretions, which had a subangular blocky shape and seemed to be soil aggregates cemented or hardened by lime; in the valley bottoms the aggregates tended to be softer. The zones of accumulation, in which the lime contents exceeded 15%, had a thickness of 10-20 cm and occasionnally 30 cm; a calcic horizon was therefore usually found. It should be recognized that the lime percentages have been estimated exclusively from soil material, including very fine concretions, that had passed through a 1.7 mm sieve; in the zones of accumulation, the fraction > 1.7 mm consisted almost entirely of lime concretions; this means that in such cases actual lime contents were

[1] available at the Dept. of Tropical Soil Science, Agricultural University, Wageningen, Holland.

111.

Table 7 : chemical data BARSEK profiles

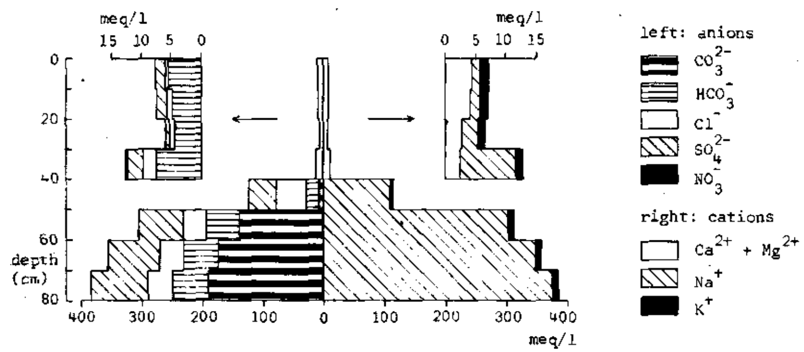
profile, depth (cm)	SP	pH_p	pH_e	EC_e	milliequivalents/l of the saturation extract Na^+	K^+	Ca^{2+}	$Ca+Mg^{2+}$	Sum +	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Sum -	% Lime
BARSEK I (flank, 12 km west of Lemuta Hill about 2,5 km inside the Park boundary)																
0-10	54.0	8.28	8.32	0.64	1.65	1.10		4.41	7.16	-	5.54	0.27	1.56	-	7.37	
10-20	54.5	8.37	8.35	0.66	1.70	1.10		4.21	7.01	-	4.84	0.89	1.58	-	7.31	
20-30	55.3	8.48	8.35	0.59	2.52	0.98		2.74	6.24	-	4.56	0.75	0.83	-	6.14	
30-40	54.0	8.82	8.59	1.08	9.04	0.80		2.61	12.45	-	7.43	2.30	2.50	0.25	12.48	
40-50	45.5	9.60	9.51	10.10	110.87	3.81		0.84	115.52	6.33	23.99	47.02	45.89	-	123.23	
50-60	51.2	10.29	10.21	22.80	303.49	8.75		0.17	312.41	137.60	55.55	37.25	72.53	0.25	303.18	
60-70	49.9	10.40	10.31	25.70	347.83	9.41		0.0	357.24	172.74	57.12	38.96	85.16	0.25	354.23	
70-80	47.8	10.46	10.37	27.20	375.65	9.36		0.0	385.01	189.36	57.02	40.17	95.23	0.25	382.03	
BARSEK II (flank)																
0-10	54.3	8.12	7.96	0.98	1.32	1.33	5.33	8.16	10.81	9.09		0.57	1.13		10.79	1.75
20-30	58.0	8.24	7.73	0.80	2.49	1.10	4.71	5.71	9.30	7.02		1.24	1.28		9.54	7.66
40-50	47.6	9.93	9.92	16.04	177.39	6.37	1.03	1.16	184.92	73.35		44.80	69.66		187.81	15.89
60-70	51.6	10.27	10.27	27.20	351.30	9.82		0.27	361.39	228.31		41.88	90.75		360.94	12.67
80-90	48.1	10.31	10.31	27.50	370.43	9.51		0.27	380.21	239.05		38.76	91.03		368.84	14.03
BARSEK III (flank)																
0-12.5	55.6	8.21	8.14	0.64	1.11	0.95	4.39	5.35	7.41	3.64				-		2.03
12.5-25	62.7	8.37	8.15	0.53	1.55	0.95	4.50	5.46	7.96	4.85				-		7.35
25- 35	56.3	8.59	8.50	0.68	4.72	0.92	5.51	6.89	12.53?	6.55				-		11.22
35- 45	45.7	9.04	9.17	1.40	15.04	1.27	?	?	16.31?	22.14?				-		17.61
45- 60	48.3	9.50	9.58	4.42	48.26	1.36	0.41	0.47	50.09	23.28				-		14.01
60- 70	51.6	9.98	9.99	10.40	122.17	2.82		0.20	125.19					-		11.33
70- 75	48.1	10.14	10.11	15.60	194.78	5.00		0.20	199.98	107.38				0.50		21.05
75- 90	57.4	10.33	10.30	20.00	259.13	7.21		-	266.34	157.07				0.75		15.58
90-105	62.2	10.32	10.30	21.40	284.35	8.13		-	292.48	170.27				0.75		8.68
105-120	45.2	10.42	10.40	22.70	306.52	8.88		-	315.40	173.08				1.00		5.87
120-140	44.5	10.44	10.41	23.40	314.35	9.55		-	323.90	172.97				1.00		3.01

Table 8 : chemical data

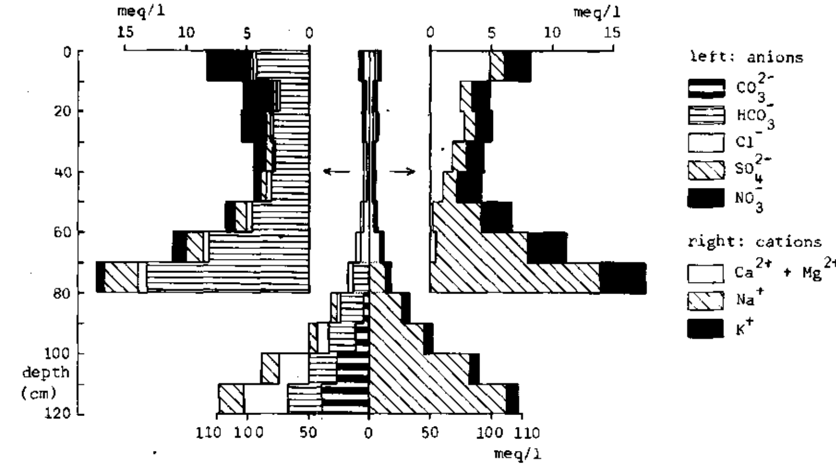
SEK-NE (South-East Kopjes - North East, Valley bottom)

depths (cm)	SP	pH_p	pH_e	EC_e	milliequivalents of the saturation extract Na^+	K^+	$Ca+Mg^{2+}$	Sum +	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Sum -	% Lime
0- 16	63.7	7.36	8.04	0.55	0.74	1.73	3.72	6.19	4.21	0.48	1.50	-	6.19	0.36
16- 30	59.8	7.40	8.13	0.43	1.30	1.10	2.27	4.67	2.83	0.45	1.39	-	4.67	0.23
30- 40	60.1	7.76	8.32	0.40	1.10	1.11	2.27	4.48	3.24	0.22	1.02	-	4.48	0.34
40- 55	59.7	8.07	8.45	0.39	1.85	0.87	2.10	4.82	3.45	0.19	1.18	-	4.82	2.09
55- 70	52.3	8.21	8.62	0.58	5.21	0.54	1.83	7.58	5.38	0.22	1.98	-	7.58	2.19
70- 90	51.0	8.17	8.63	0.73	6.74	0.49	1.32	8.55	5.38	0.43	2.74	0.0	8.55	1.24
90-110	47.4	8.01	8.60	0.75	6.52	0.80	1.22	8.54	3.78	0.43	2.33	2.00	8.54	2.90
110-130	44.8	8.12	8.70	0.96	9.52	0.83	1.28	11.63	5.94	0.53	3.16	2.00	11.63	3.78
130-150	47.2	8.29	8.80	1.25	13.13	0.96	1.56	15.65	9.18	1.15	3.32	2.00	15.65	2.75
150-170	47.9	8.29	8.64	3.50	34.35	1.49	1.05	36.89	6.00	22.50	6.89	1.50	36.89	2.26
170-190	51.2	8.12	8.52	5.53	53.04	1.76	1.66	56.46	4.28	43.08	8.35	0.75	56.46	2.14
190-210	50.5	7.90	8.32	8.00	72.17	2.47	3.31	77.95	3.35	62.50	11.60	0.50	77.95	0.96
210-230	52.2	7.80	8.27	9.00	81.74	3.16	5.14	90.04	2.83	73.56	13.40	0.25	90.04	1.19
230-250	50.5	7.77	8.37	10.00	92.61	3.53	7.00	103.14	2.62	79.62	20.40	0.50	103.14	0.75

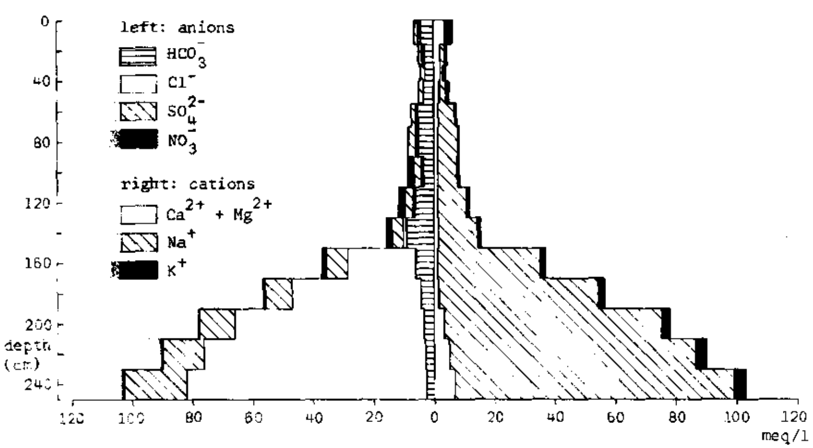
Fig.15: Salinity patterns and salt composition in 4 profiles of various relief positions within soil landscape I.1 (Short grasslands): ion concentrations in milliequivalents per litre of the saturation extracts.



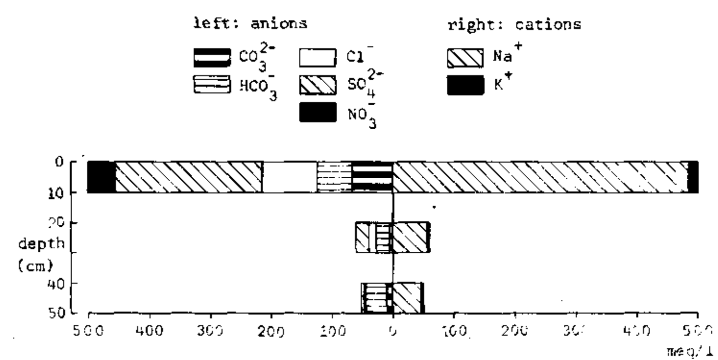
a: **BARSEK** (gently undulating plain; near eastern Park boundary).



c: "Zebra" kopjes (profile on upper flank near the "Zebra" kopjes).

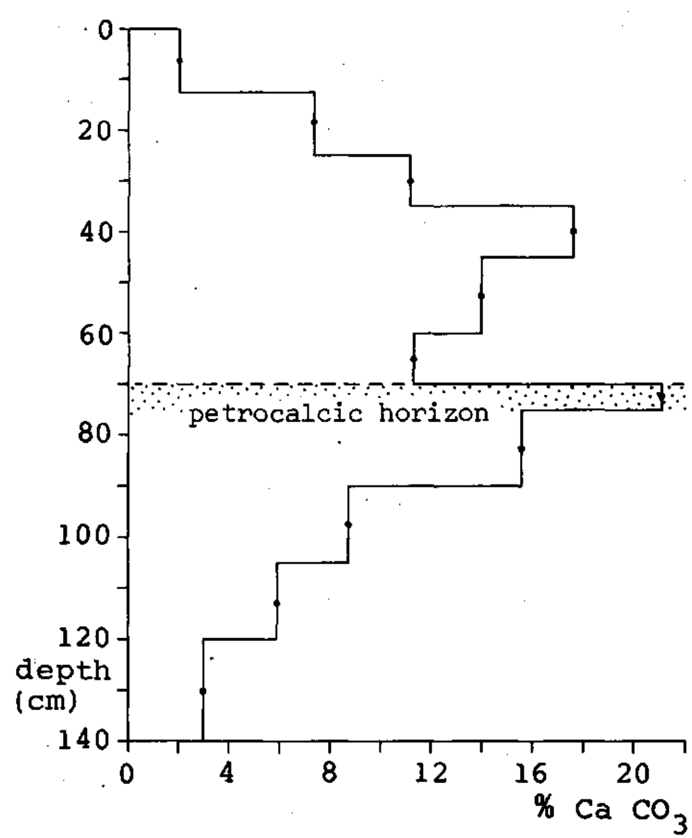


b: **SEK-NE** (valley bottom, near the South-east kopjes).



d: Gol kopjes, slick spot (flat plain, near Gol kopjes, *Sporobolus kerblei* spot).

Fig./6: Distribution of lime throughout the BARSEK III profile; lime contents as weight percentages of the soil fraction < 1.7 mm.



- Salt composition

In the top 30-40 cm of the non-saline soils and in the non-saline topsoils of the internally salt-affected soils, soluble Ca, Mg and K constituted more than 50 per cent of the totals of cations.
At lower depth, and with increasing EC_e-values - especially in the B-profiles, which supported a sparse cover of grasses other than *Andropogon greenwayi* -, soluble Na became rapidly the dominant cation.
In the moderately and strongly saline subsoils of the B-profiles at the Golzu, NaNae and NaNo-sites, the solubility of Ca and Mg ions had become negligibly low as a result of the high pH; soluble K was an important component amounting up to 10 per cent of the totals of cations.
Bicarbonate was the dominant anion in the non-saline parts of the soil profiles (except for the NaNo flank - B profile). In the strongly saline subsoils of the Golzu I-B, II-B, NaNae 3-B and Nazu profiles, carbonate plus bicarbonate amounted 50 per cent or more of the sum of cations (Golzu I-B!). In the upper part of the saline subsoils chloride concentrations were relatively high; in the NaNo-B profile (40-50 cm) chloride was even the dominant anion.
The relative accumulation of chloride in the upper part of the saline zone within a soil profile has already been described for various soils of the short grasslands.
Nitrate was found in several profiles at varying depth and in varying concentrations.
At the NaNo-site (NaNo I-V and NaNo VI-IX series) high nitrate concentrations were found in samples collected from termite mounds.
Special attention to the accumulation of nitrate in termite mounds has been paid in Ch. 3 : Special features.

Since the particle size distribution was fairly constant throughout the various horizons (see Table 5 -BARSEK) and the organic matter content decreased strongly at increasing depth, the increase of the CEC has to be contributed to other factors such as:

1. increase of the pH; the amorphous materials present have CEC values that are positively correlated with the pH (Aomine & Jackson, 1959; Van Reeuwijk and De Villiers, 1970).
2. increase of the chabazite content, which, in fact, was found in the BARSEK profile; chabazite has a high exchange capacity and exchange processes take place in accordance with the lyotropic series of replacement (Barrer, 1958; Ames, 1961, in Van Reeuwijk 1974).

CEC values, obtained by using a modified method after Bascomb (see Part I, 2: Methods) were found to be equal for the 20-30 and 40-50 cm samples; both, however, were lower than the CEC of the 20-30 cm sample obtained according the standard method. The modified Bascomb method was expected to give results that would remain unaffected by possible interference by Na_2CO_3 and $CaCO_3$. If the above results were correct, the higher CEC values obtained by using the standard method might be explained by the assumption that during the last stage of the exchange process (percolation of the sample by 1 ammonium acetate) a more complete exchange had taken place or that more Na^+-ions (and other cations) had been leached out by the dissolution of easily weatherable minerals. An indication for this might be the presence of a substantial amount of K^+-ions in the final percolate (actually, only Na^+ should have been present).
Further discussions on this subject will be given in Van der Plas, Van Reeuwijk and De Wit (in prep.).

Table 9: CEC-values and exchangeable cations in various soils of soil landscape I.1 (Short grasslands), all in meq/100 g of soil.

	BARSEK II[1]				Lemuta profile[2]			topsoils[3]	
depths (cm)	0-10	20-30	40-50	60-70	0-15	15-32	60-90		
Na	1.21	2.18	53.44	75.48	1.17	3.46	46.70	2.9	Na
K	11.99	11.86	23.53	26.87	11.44	11.93	21.70	1.6	K
Ca	38.76	37.51	4.13	2.40	61.1	62.7	59.3	36.9	Ca
Mg	3.64	5.63	1.35	0.49	4.6	7.0	6.8	4.4	Mg
total	55.60	57.18	82.45	105.24	78.31	85.09	134.50	45.8	total
CEC	54.62	54.35	73.91	95.05	44.8	44.2	57.3	-	CEC
CEC*	-	43.03	45.19	-	-	-	-	-	

1) Na^+ and K^+ leached by 1 N NH_4-acetate, Ca^{2+} and Mg^{2+} by 1 N Na-acetate; CEC determined by displacement of adsorbed Na^+ by 1 N NH_4^+-acetate.
CEC* determined according to "modified Bascomb method" (see Part I, Ch. 2: Methods).
The amounts of exchangeable bases have been corrected for soluble salts.

2) "Calcimorphic soil with hard pan" given by Anderson & Talbot (1965); all bases leached by 1 N NH_4^+-acetate at pH=7.0; CEC determined by displacement of adsorbed NH_4^+ by 1 N K_2SO_4.

3) Mean values for top soils of 8 sites in the eastern Serengeti Plain, given by Anderson & Talbot (1965); bases extracted by 0.03 N H_2SO_4 in 0.1 HCl.

-Exchangeable cations; base saturation

Data have been given in Table 9.

In the non-saline top 40 cm of the BARSEK profile, exchangeable Ca^{2+} and Mg^{2+} formed roughly 75% of the total bases, while the Na^{+} percentage was almost negligible; the relative amounts of K^{+} were important (over 20% of the total). In the saline and alkaline parts from 40 cm down to the petrocalcic horizon nearly the opposite was found: the relative amounts of Na^{+} increased up to 70%, K^{+} went up to amounts of over 25%, while the relative amounts of Ca^{2+} and Mg^{2+} had become very low in the layer just above the petrocalcic horizon due to displacement by the high Na^{+} concentration in the soil solution and the very high pH (10,3) by which the activity of the Ca^{2+} and Mg^{2+} ions had become very much reduced.

The base saturation was 100% throughout the profile while the total of the bases exceeded the CEC ("oversaturation"), especially in the strongly saline-alkaline part of the profile. The data of the Lemuta profile, given by Anderson & Talbot (1965), showed the same tendencies; the amounts of exchangeable Ca^{2+}, however, were much higher while the "oversaturation" was even more pronounced. The "top soil" data (Anderson & Talbot, 1965) were also quite comparable with those of the surface layers of the BARSEK and Lemuta profiles, except for the amounts of exchangeable K^{+}.

The oversaturation found for the BARSEK samples are probably due to incorrect - i.e. too low - figures for the cation exchange capacity. This can be explained as follows: During the first stage of the CEC experiment, in which the exchange complex was saturated with Na-ions (using Na-acetate), an incomplete replacement of K by Na may have taken place. In the final stage, in which Na was displaced by NH_4-ions (using NH_4-acetate), the amount of Na found in the percolate did not equal the CEC as in the same percolate also substantial amounts of K were found: Evidently the K-ions, which had not been displaced in the first stage, became displaced in the final stage. The CEC values were therefore probably too low. The replacement of exchangeable K and Na by NH_4-ions (NH_4-acetate) - as applied in the first stage of the second experiment - was likely to be much more complete. The combination of the results from the first (CEC) and the second experiment did probably lead to the oversaturation.

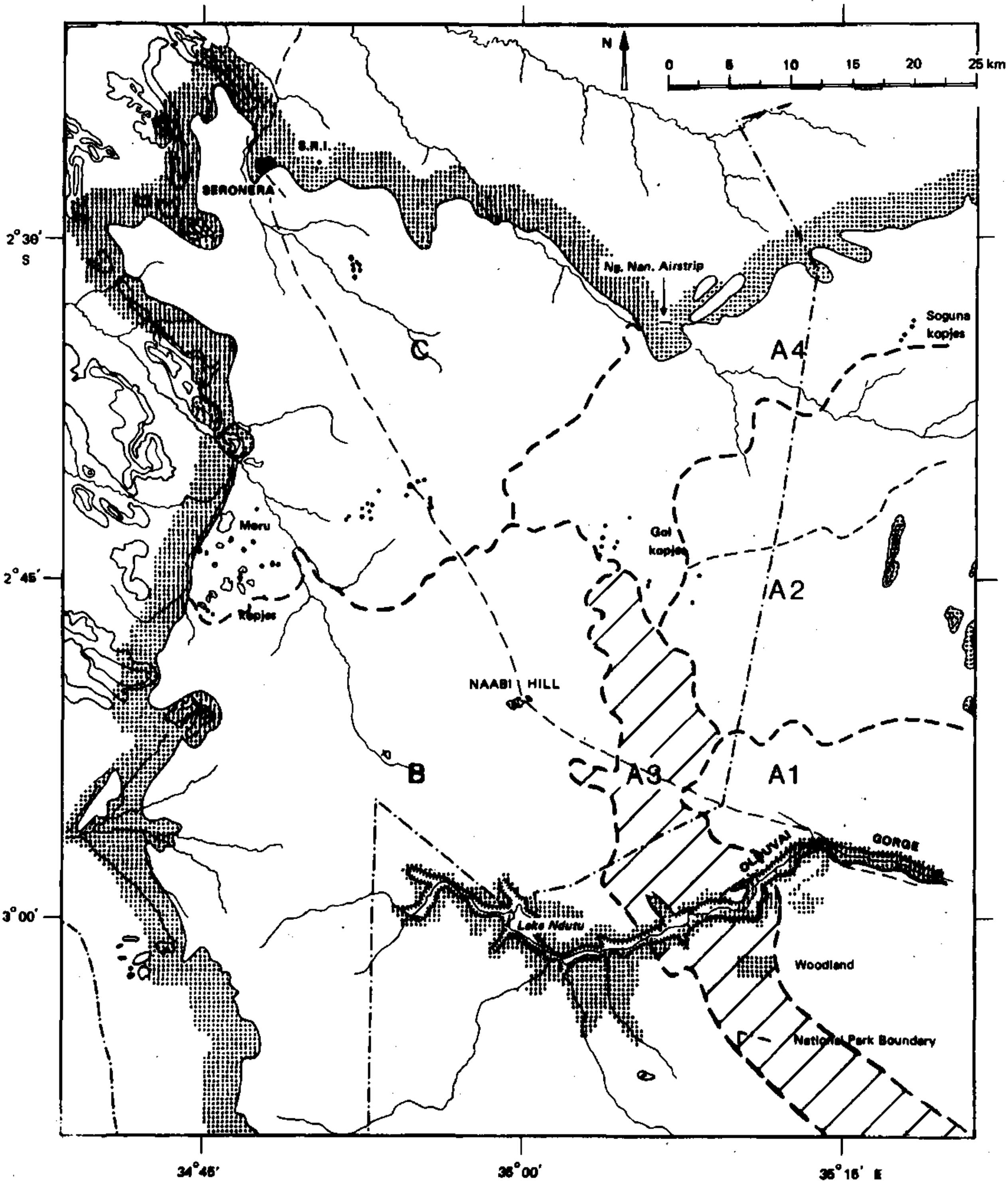
This picture agrees with results obtained by Van Reeuwijk & De Villiers (1968) from their investigations on potassium fixation by synthetic amorphous aluminosilica gels: "The larger the solvated size of the replacing cation, the greater was the amount of K retained". The replacing power followed the lyotropic series: $NH_4 \gtrsim K > Na > Ba > Ca > Mg$.

In the Lemuta profile the oversaturation was even more pronounced. In view of the methods applied to these samples (NH_4-ions used in the first stage and K-ions in the final stage) the explanation has to be a different one. The most likely explanation is found in the very high figures for exchangeable Ca, especially for the samples collected at lower depth. At lower depth high amounts seem incompatible with the strong salinity and high pH in this profile (high amounts of sodium carbonate and bicarbonate in the soil solution!).

Probably considerable amounts of $CaCO_3$ had been dissolved during the first stage (percolation with NH_4-acetate). This process could even take place in highly alkaline samples because the pH was kept constant at 7.0 during percolation.

To reduce the interference on the determination of exchangeable Ca (and Mg) caused by the dissolving of $CaCO_3$, exchangeable Ca (and Mg) were determined by the present author in percolates obtained by leaching the soil with Na-acetate in which case the pH remained well over 8.0.

Fig 17: Location of the A.3 area



was a marked increase of the clay content; the C-material (below 114 cm) resembled the soil material in the upper parts of the C-horizons of the other profiles discussed.

Comparing the figures found for the "calcimorphic soils with soft pan" given by Anderson and Talbot (1965) for the dark top soils of the NaNo-A and B with those of the NaNo-A and B and the Na-lag profiles (Table 15) - the latter profiles were all situated within the zone of the "calcimorphic soils with soft pan" as marked by Anderson & Talbot (1965) - the clay contents in the calcimorphic soils were found to be much lower, the percentage of sand much higher. The same applies to the figures of the NaNo-S (valley bottom) profile and those of the "vertisol of lithomorphic origin", although clay contents in the latter profile were comparatively somewhat higher than in the calcimorphic soils with soft pan. The strong differences between the Oosterbeek figures and those given by Anderson & Talbot can be explained from the different methods used for the mechanical analysis (See Part I, Ch. 2: Methods).

The effect caused by different analysis procedures is shown by data obtained from NaNo-A (0-25 cm layer) and NaNo-B (80-100 cm layer) samples, which had been handled in a different way.

Between the NaNo-A 0-25 cm samples the differences in clay content was small, but in case of the highly calcareous NaNo-B 80-100 cm sample a considerably higher clay content was found when the sample was pre-treated with sodium-EDTA to dissolve the lime. This indicated that the latter sample contained an important percentage of amorphous material, and possibly also zeolites, that apparently did occur in the finest fraction only. By the pre-treatment with HCl, a part of the amorphous material and all zeolites (if any) became probably dissolved, which resulted into a lower clay percentage.

The mean annual rainfall increased from 550 mm in the east to 650 mm in the west over a distance of about 10 km; the gradient was one of the steepest within the entire study area (see Part I, Ch. 3: Climate).

2.1.3.2. Morphology

No actual data on soil structure were recorded since all profiles investigated had been sampled by auger.

To judge from the moderate angular blocky structure in the top 40 cm, recorded in a soil pit inside the soil landscape I.2 close to the boundary between I.2 and the A.3 area, there must have been a relatively strong increase of structure development across the A.3 area from the east to the west, which may be linked with the strong increase of mean annual rainfall in this area. Chemical data, discussed below, support this point of view.

The most important feature was the gradual disappearance of the petrocalcic horizon. It still occurred in the sloping south-east part near the Olduvai Gorge; further northwards, e.g. along the Ndutu Road and Main Road (Nanae sites) the petrocalcic horizon was found replaced by a zone of strongly cemented lime concretions at depths below 70-80 cm; the concretions varied in size from fine to coarse; the coarse lumps resembled pieces of petrocalcic horizon material that occurred further eastwards (A.1 , A.2 areas).

2.1.3.3. Physical properties, mineralogy

Soil texture, porosity, mineralogical composition and water retention characteristics are likely to be similar to those of the soils of the A.2. area (BARSEK!); for estimation of the permeability, the data obtained at the Gol kopjes exclosure and Zebra kopjes (both sites situated in A.4) may be considered as representative.

2.1.3.4. Chemical characteristics

- Salinity and Alkalinity

Table 10 and Appendix 9[1] show chemical data from several profiles within the A.3 area. Besides correspondence with the salinity and alkalinity patterns found for soils within A.2 there were also some differences:

a. High pH and EC_e values were found at greater depths (i.e. below 60-80 cm); pH-paste values in the top 40-60 cm varied between 7.0 and 8.5, which was about 1.0 pH unit[F] than in the A.2 profiles; pH values of the saturated soil pastes were always lower than those of the extracts.

b. Strong variation in subsoil salinity over short distances; profiles that were non-saline throughout the upper 100-120 cm, were quite common, especially near the boundary with soil landscape I.2. The non-saline spots could easily be distinguished from the saline soils by the different composition of the grassland vegetation and the difference in soil cover compared with the typical "short grassland" (see Part III: Vegetation and soils); some examples have been given in the Table 10 and Appendix 9[1].

c. Frequent occurrence of external salinization inside and around the slick spots, marked by the presence of salt-tolerant grasses. The slight difference in height between bare spot and its surroundings had apparently caused the accumulation of soluble salts-leached by rainwater from its surroundings and carried towards the spot by surface and subsurface transport.

   About the origin of the slick spots one can only speculate. They may have originated by wind erosion, e.g. because of different soil texture, a more open vegetation cover, or by activities of wild animals such as scraping of hoofs (ungulates, searching for salts?) or animals turning

F: lower

1 available at the Dept. of Tropical Soil Science, Agricultural University, Wageningen, Holland.

Table 10 :

chemical data

<u>NaNae-A</u> (flat plain, tall Cynodon dactylon spot)

depth: (cm)	SP	pH_p	pH_e	EC_e	Na^+	K^+	$Ca^{2+}+Mg^{2+}$	meq/l Sum+	CO_3^{2-} $+HCO_3^-$	Cl^-	SO_4^{2-}	NO_3^-	meq/l Sum −	% Lime
0– 20	51.0	7.43	8.08	1.30	4.96	2.39	6.80	14.15	12.12	1.17	1.14	-	14.43	0.52
20– 40	38.1	8.05	8.74	1.60	16.70	1.25	1.73	19.68	13.81	0.81	-	-		2.97
40– 60	38.0	8.71	9.00	2.06	23.87	2.07	- 1)	25.94	26.03	1.34	-	-		7.30
60– 80	41.0	9.18	9.42	2.69	33.39	1.96	- 1)	35.35	33.61	1.54	-	-		7.52
80–100	40.9	9.38	9.57	3.35	50.22	1.96	- 1)		39.46	2.05	-	-		11.60
100–120	39.0	9.57	9.70	4.01	51.13	2.50	- 1)	53.63	46.35	3.07	-	-		14.88

<u>NaNae-B</u> ("typical" Short grassland with <u>Sporobolus</u> <u>marginatus</u> etc.)

depth: (cm)	SP	pH_p	pH_e	EC_e	Na^+	K^+	$Ca^{2+}+Mg^{2+}$	meq/l Sum+	CO_3^{2-} $+HCO_3^-$	Cl^-	SO_4^{2-}	NO_3^-	meq/l Sum −	% Lime
0– 20	49.6	7.33	7.91	0.94	2.78	1.53	6.27	10.58	7.16	1.74	0.66	-	9.56	0.56
20– 40	52.8	7.47	7.76	6.70	28.26	3.53	39.06	70.85	3.75	58.49		-		2.32
40– 60	47.8	8.62	8.54	29.00	333.91	13.62	18.00	365.53	7.71	187.75	171.56	-	367.02	5.63
60– 80	47.1	10.30	10.30	29.70	387.83	12.28	- 1)	400.11	144.42	120.00	129.38	-	393.80	7.04
80–100	44.0	10.26	10.25	26.20	333.91	11.04	- 1)	344.95	131.41	97.25		-		10.06

1) extracts too dark for proper analysis.

<u>NaNae 2</u> ("Short" grass, flat plain)

depth: (cm)	SP	pH_p	pH_e	EC_e	Na^+	K^+	Ca^{2+}	$Ca+Mg^{2+}$	Sum +	CO_3^{2-} $+HCO_3^-$	Cl^-	SO_4^{2-}	NO_3^-	Sum −	Lime %
0– 20	47.8	7.57	8.28	0.76	1.70	1.35	4.40	5.22	8.27	6.31	0.53	0.55	-	7.39	0.53
20– 40	49.8	7.94	8.31	0.58	2.37	0.83	2.68	3.23	6.43	4.01	0.23	0.44	-	4.68	2.91
40– 60	42.5	8.25	8.99	1.44	13.57	0.92	0.75	0.88	15.37	7.22		3.70	-		5.20
60– 80	43.6	9.19	9.33	10.20	100.87	4.50		0.94	106.31	15.85	49.50	39.59	-	104.94	9.03
80–100	43.4	10.11	10.22	16.40	179.13	7.89			187.02	84.21	47.45	56.30	1.50	189.46	12.95
100–120	41.9	10.12	10.20	16.40	178.26	8.13			186.39	80.44	43.50	55.54	3.50	182.98	18.31
120–140	41.5	9.80	9.90	12.60	136.09	6.49			142.58	42.36	42.30				13.82

Table 11 : cation exchange capacity and exchangeable cations in the NaNae 2 profile (soil landscape I.1, A.3 area)

NaNae 2

CEC, ESP etc. (corrected) in meq/100 g

	CEC	Na^+	K^+	Ca^{2+}	Mg^{2+}	Total Bases	"H^+"
0- 20	44.29	0.93	8.96	30.53	4.19	44.61	-
40- 60	42.39	9.36	9.36	22.77	5.29	46.78	-
80-100	52.44	37.89	18.65	2.18	0.78	59.50	-

Percentages:

	CEC	% Na	% K	% Ca	% Mg	Base Sat.	% "H"
0- 20	44.61=TB	2.08	20.09	68.44	9.39	100.00	-
40- 60	46.78=TB	20.01	20.01	48.67	11.31	100.00	-
80-100	59.50=TB	63.68	31.34	3.66	1.31	99.99	-

ESP, estimated from SAR versus ESP from experiment:

	Ca + Mg (meq/l)	Na (meq/l)	SAR	ESP	ESP (exp.)
0- 20	5.22	1.70	1.05	0.29	2.08 (2.10)
40- 60	0.88	13.57	20.46	22.43	20.01 (22.08)
80-100	0.25?	179.13	506.66	88.18	63.68 (72.25)

themselves around in the dust or mud; the latter has been observed several times. Another possibility might be the disappearance of the vegetation as a result of increased salinization - the latter, for instance, might be due to different soil textures - followed by erosion processes as mentioned before.

At the base of the scarps similar situations have been recorded. Chemical data for the above situations will be discussed under Soils of the A.4 area.

- CEC, exchangeable cations

Table 11 shows data obtained from NaNae 2 samples. CEC figures and amounts of exchangeable cations resembled those of the BARSEK II data and the figures for the Lemuta profile, given by Anderson & Talbot (1965) (Table 9). The CEC values of the subsoil (80-100 cm) were somewhat lower than in the BARSEK profile, which might be due to lower contents of amorphous materials or chabazite.

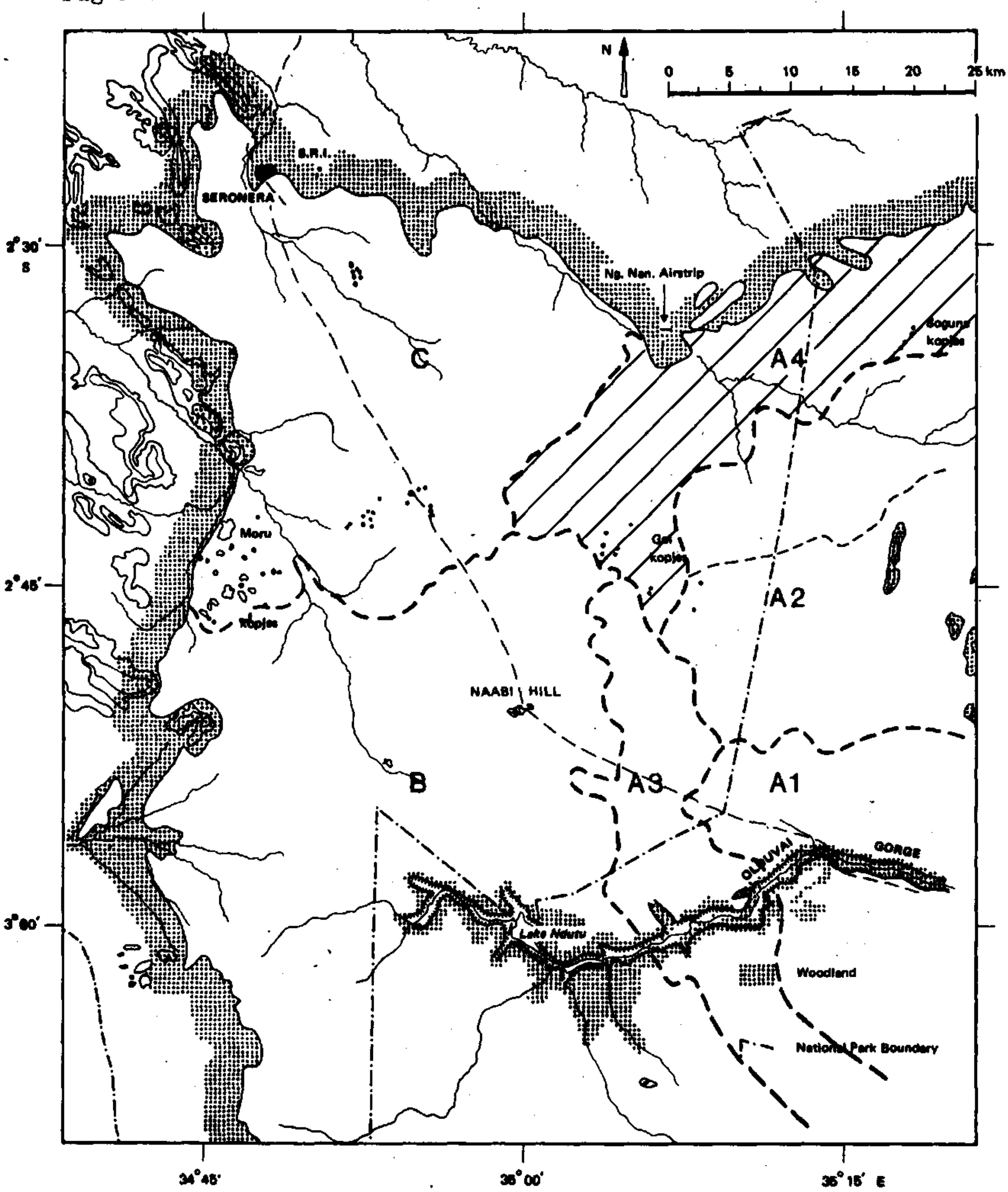
- Lime

Contrary to the situation in the A.2 area, the lime percentages in the top soil (0-20 cm layer) were lower than 1%, while the zones of maximum accumulation were found at a considerably lower depth.

To judge from the increase of the lime percentage with the depth, a calcic horizon is likely to occur in most profiles (samples below a depth of 80-100 cm could hardly or not be collected because of the abundant occurrence of hard and coarse concretions at that depth (see Morphology).

The disappearance of the continuous phase of the petrocalcic horizon, the increased thickness of a saltfree top soil combined with a lower alkalinity, and the progressed decalcification, can only be attributed to a more intensive leaching as a result of the sharply increasing mean annual rainfall in this area (Part I, Ch. 3: Climate).

Fig 18: Location of the A.4 area

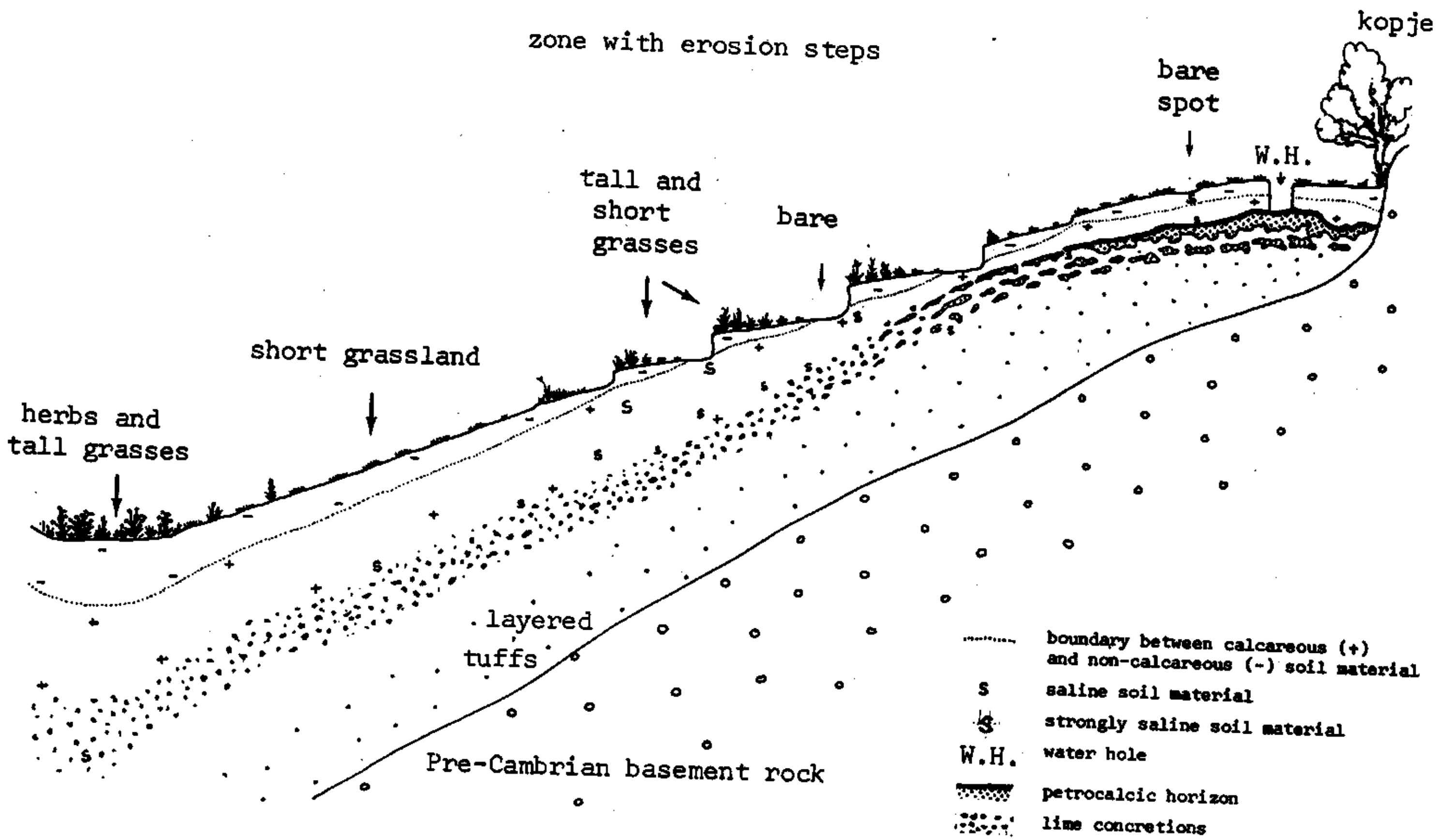


2.1.4. Soils of the A.4 area (Sametu-Soguna area)

2.1.4.1. Landscape and topography

The area coincides with the Landsystem-associations 14.14 to 14.19 (Gerresheim, 1974). The topography is gently sloping or gently undulating. A striking feature form the so-called "erosion steps" or "erosion terraces", which occur abundantly on the flanks of the ridges. The steps are miniature escarpments that vary in height from a few centimetres to 1 metre and are in many respects comparable with the low scarps discussed under 2.1.3.
Viewed from the air the steps often had arc-like shapes and appeared - contrary to the scarps - to run parallel to the contours. Their origin seems to be connected with the nature of the landscape, namely the stronger slope gradients and certain physical-chemical properties of the soil. Special attention to "step-erosion" is paid in Ch. 3 : Special features).
In this area a large number of kopjes is found: outcrops of the Pre-Cambrian basement. Most of them consist of Sametu Gneisses of the Serengeti Group (Pickering, 1958, 1960) and often occur in lines or clusters on top of the ridges, e.g. several groups of the Gol kopjes, the so-called Zebra kopjes, the Barafu kopjes and the Soguna kopjes in the north-east; a smaller number was found on flanks or in the valleys.
Exposures of the basement are also found in some deeply incised valleys of the Magungu River and its side arms.
Another deep but differently shaped valley - long slopes with a weak gradient - originates between the Gol and Zebra kopjes and runs towards the north-west; although no outcrops of the basement rock are found on its flanks, substantial amounts of reddish "sandwash" (very fine quartz gravel or very coarse quartz grains), that cover the bare flat valley bottom, indicate the presence of residual materials in the adjacent soils.

Fig.19 : Soil landscape I.1 (Short grasslands): A.4 area; cross section near "Zebra" kopjes.



The soils still belong to the soil landscape I.1, but,going from the south-east towards the north-west,they change gradually into the soils of soil landscape I.3 (Long grasslands) and into the soils of the Dissected Plain (II.1). Most common soil units were:loamy soils of ridges and the gently undulating plain, with a petrocalcic horizon deeper than 50 cm or without a petrocalcic horizon (I.1.1.2 , I.1.1.3), soils of flanks with a petrocalcic horizon deeper than 50 cm or without one (I.1.2.2), locally marked by "step" erosion (I.1.2.2 s) . Within the A.4 area and especially within the Sametu area many waterholes occur on top of the ridges; most had well developed scarps facing the east with a weak crest, consisting of blown out material, at the top.

The Short grassland vegetation in this area included several species that were characteristics for the so-called "Long" grasslands e.g. Pennisetum mezianum and Themeda triandra; their physiognomy, however, was always fairly short (up to 20-30 cm). In the deeply incised valleys of the Magungu River some Acacia trees were found.

The mean annual rainfall increased from 450 mm in the north-east to 600 mm in the west; contrary to the situation in the A.3 area the rainfall gradient was fairly weak (Part I, Ch. 3: Climate).

2.1.4.2. Morphology

Fig.19 shows a catena near the Zebra kopjes; a profile situated in the upper part of a flank has been described (Appendix 10).

- Structure, porosity

  In the Zebra kopjes profile the soil structure was found to be even weaker developed than at BARSEK; a more strongly developed soil structure may be found in the soils of the lower flanks and valleys, especially near the boundaries with soil landscapes I.3 and II.1 , where soil textures are much more clayey than in corresponding soil units in the A.2 and A.3 areas. Like in most of the other parts of soil landscapes I.1 the porosity could be characterized by the term "sponge" structure (Zebra kopjes profile)

- Petrocalcic horizon

Petrocalcic horizons were found in soils of some ridges, in areas adjacent to the valleys of the Magungu River and around the deep valley and the waterhole between the Gol and Zebra kopjes. Along the steep walls of the Magungu valley petrocalcic horizons outcropped at various levels (aerial photographs!); they may be correlated with older ash deposits. On the ridges and the nearly flat plain the petrocalcic horizon was found at depths of 50 cm or more (I.1.1.2 , I.1.1.3); locally, e.g. in the areas mentioned before, however, also within 50 cm (I.1.1.1). Down the slope the petrocalcic horizon was found replaced by a dense layer of hard concretions (I.1.2.2) that could be perforated by a soil auger. In the Zebra kopjes profile this layer was found between 70 and 80 cm depth. In a transect along the eastern Park boundary (sites 18-24) the profiles of the ridges were deep and a petrocalcic horizon appeared to lack within 1.20 m (I.1.1.3); instead of it a zone of concretions was found. In one place a weakly cemented soil layer was recorded at a depth of 80 cm; it had a thickness of a few cm and could be perforated easily by augering; this thin "pan" was covered by a horizon rich in concretions and might be the initial stage of the formation of a petrocalcic horizon (N.B. lime percentages exceeded 15%). It is uncertain whether the above situation is relevant for all ridge soils throughout the Soguna region, since on the ridge just south-west of the Soit Ayai Park Entrance a petrocalcic horizon was found exposed in waterholes. On the lower flanks and in the valley bottoms no petrocalcic horizon was found within 1.20 m; also the lime concretions had become less abundant and occurred mostly at depths below 70-80 cm.

- Gravel

In a number of places, especially on the ridges in the north-east along the boundary between soil landscapes I.3 (Long grasslands) and II.1 (woodlands), rounded medium sized pieces of quartz gravel, up to 5 cm diameter, were found; they occurred on the soil surface and also in even larger quantities at lower depths (50-60 cm), probably just on top of a petrocalcic or calcic horizon.

F also Quartz pebbles were F found embedded in exposed petrocalcic horizons, e.g. on eroded upper flanks and ridge tops in the area between the eastern Park boundary and Lemuta Hill.

2.1.4.3. Physical characteristics

- Soil texture: only a few remarks can be made: soil textures of the ridge soils were not very different from those of the ridges elsewhere in soil landscape I.1. The soils of the flanks and valley bottoms were finer textured than those in the other parts of the Short grasslands; the differences were most clear near the boundaries with the soils of the Dissected Plain (broad soil landscape II) and those of the so-called transitional zone, in which the soils are intergrades between units (of corresponding relief position) belonging to soil landscapes I.1 (Short grasslands) and I.3 (Long grasslands).
- Infiltration: infiltration measurements have been made at 2 sites (surface soil only): at the Zebra kopjes site (upper flank, near the soil pit) and near the Gol kopjes enclosure (flat plain). Data have been given in Fig.14a and Appendix 5. The infiltration rates at both sites (surface soil) were almost equal; they were, however, about 1.5 times lower than the values, found for the SEK-NE and BARSEK-sites (Lemuta area) which might be attributed to the presence of a thicker

or denser surface crust at the Zebra kopjes and Gol sites. The latter fact may be linked up with the higher mean annual rainfall in these places (see Part I, Ch. 3: Climate).

2.1.4.4. Chemical characteristics

- Salinity and Alkalinity

Table 12 shows some figures from a catena that formed part of the eastern Park boundary transect. The salinization and alkalinity patterns throughout the soil profiles and catena generally resembled situations described before, viz. in the Lemuta area (A.2):
internal salinization and a positive correlation between pH and salt contents (sodium carbonate!). pH-values (paste) in the non-saline top soils varied between 6.7 and 8.5; these values were somewhat lower than those found for comparable situation in the A.1 and A.2 areas.
The lower pH values are the result of decalcification and a more intensive leaching of soluble salts from the topsoil due to the increased mean annual rainfall (see also "Lime"). The decalcification was most pronounced in the valley bottom profile (site 21, Table 12).
The highest salinity was found in profiles that were situated halfway the flanks; the thickness of the non-saline top soil increased rapidly from the lower flank downwards into the valley bottom.
Besides internal salinization, also small,isolated,partially bare spots ("slick spots") with external salinization were found on the ridge tops and upper flanks, especially in parts marked by "step erosion".
Another transect, situated further westwards, appr. 2 km south of the Zebra kopjes in a typical step-erosion area, included several sites on the ridge top and the upper flank. Data from the selected sites have been listed in Appendix 11[1]. Chemical data for the Zebra kopjes profile (soil pit) are given in Appendix 13;

[1] available at the Dept. of Tropical Soil Science, Agricultural University, Wageningen, Holland.

Table 13 : chemical data

Gol SRI

depth (cm)	SP	pH_p	pH_e	EC_e	Na^+	K^+	$Ca^{2+}+Mg^{2+}$	Sum +	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Sum -	% Lime
					meq/l										
0- 10	53.3	7.12	8.02	0.96	1.35	1.71	6.10	9.16	-	3.16	0.40	0.52	5.00	9.08	0.51
10- 20	50.0	7.24	7.79	0.82	1.59	1.37	4.41	7.37	-	2.75	0.43	0.48	3.75	7.41	0.13
20- 30	50.2	7.74	8.19	0.54	1.28	1.09	3.03	5.40	-	1.86	0.43	0.54	1.75	4.58	0.46
30- 40	52.4	7.99	8.21	0.57	1.42	0.97	3.12	5.51	-	1.79	1.17	0.62	1.50	5.08	1.81
40- 50	53.8	7.99	8.29	0.46	2.35	0.66	2.03	5.04	-	2.47	0.50	0.77	0.75	4.49	2.76
50- 60	51.8	8.08	8.25	0.51	3.78	0.55	1.46	5.79	-	3.30	0.40	0.77	0.75	5.22	4.01
60- 70	50.3	8.17	8.11	0.68	5.91	0.54	1.08	7.53	-	4.54	1.00	1.35	0.50	7.39	4.54
70- 80	47.0	8.26	8.43	0.94	8.83	0.64	0.88	10.35	-	5.98	1.00	1.89	0.25	9.12	6.19
80- 90	49.3	8.42	8.41	1.16	11.39	0.73	1.83	13.95	-	8.33	1.25	2.56	0.00	12.16	9.29
90-100	46.6	8.62	8.70	1.60	16.00	0.98	2.37	19.35	-	10.93	1.75	4.39	0.25	17.32	12.77
100-110	42.9	8.83	9.04	2.40	23.74	1.36	-	25.10	-	13.30	4.15	6.92	-	24.37	19.25
110-120	42.2	9.28	9.50	3.90	39.39	2.11	-	41.50	-	22.42	8.90	11.22	-	42.54	21.69

Gol K. Bare spot

depth (cm)	SP	pH_p	pH_e	EC_e	Na^+	K^+	$Ca^{2+}+Mg^{2+}$	Sum +	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Sum -	% Lime
					meq/l										
0-10	40.5	9.91	9.87	34.6	486.52	13.49	2.00	500.01	64.32	59.03	90.80	241.46	44.0	499.61	2.97
20-30	37.5	9.26	9.36	5.1	57.91	2.36	"	60.27	4.15	23.55	10.94			38.64	6.97
40-50	35.4	9.34	-	4.0	47.61	3.18	"	50.79	8.30	34.96	4.21			47.47	11.93

In view of the high salt contents in many soils of the erosion step areas, salic horizons, according to the criteria given in Soil Taxonomy (1975), are found in many places; not only in the soils that were external solonchaks but also in internally affected profiles.

In this area also profiles, that were non-saline down to a depth of 1 metre or more, were quite common, especially in the nearly flat parts and extensive shallow depressions near the boundaries with the Andropogon and Long grasslands. As an example data from a profile near the Gol kopjes close to the airstrip have been given in Table 13.

Besides the salinization and alkalinity patterns that are related with slick spots, erosion steps or scarps and relief position within a catena, there were also variations in subsoil salinity over short distances, which were comparable with situations discussed for the A.3 area (e.g. Na Nae sites, see Table 11 and Appendix 9[1]).

As a result of the leveling effect of the 2 or 3 point sampling method by auger, that was used for each of the profiles investigated (see Part I, Ch. 2: Methods), the actual variation did not stand out fully. To get some idea about it and to detect any possible vegetation-salinization relationships or coincidences, two sites have been investigated by single-point sampling:

1. Near Zebra kopjes, outside and inside cages that protected the grassland against grazing (near profile pit), upper flank
2. Gol kopjes enclosure, both outside and inside, flat plain.

Locations of the selected points and the analysis results have been listed in Appendices 14[1] and 15[1]; some mean values are given in Table 14. The selection of the sampling points had not been made randomly but it was based on the presence of certain combinations of grass species within the Short grasslands and on the knowledge (then) of relationships

[1] available at the Dept. of Tropical Soil Science, Agricultural University, Wageningen, Holland.

Table 14

I: Mean EC_e-values (mmhos/cm at 25 °C) per 20 cm layer in profiles inside and outside enclosures near Zebra kopjes and Gol kopjes.

A. Zebra kopjes (cages)

	EC_e inside cages	n[1])	lowest value	highest value	EC_e outside cages	n[1])	lowest value	highest value
0- 20	0.49	6	0.46	0.52	0.53	6	0.46	0.60
20- 40	0.46	6	0.45	0.49	0.46	6	0.41	0.49
40- 60	0.63	6	0.52	0.78	0.71	6	0.41	1.40
60- 80	2.51	6	1.10	7.40	5.56	6	1.23	14.20
80-100	7.70	6	2.41	22.00	13.54	6	3.55	28.50
100-120	13.42	6	7.00	25.80	18.25	6	10.00	31.20

B. Gol kopjes enclosure

	EC_e inside enclosure	n[1])	lowest value	highest value	EC_e outside enclosure	n[1])	lowest value	highest value
0- 20	0.64	5	0.50	0.75	0.69	8	0.48	0.88
20- 40	0.94	5	0.38	2.98	0.52	8	0.37	0.68
40- 60	2.26	5	0.63	7.10	2.65	8	0.38	8.00
60- 80	4.43	5	1.04	13.05	9.17	8	0.96	24.20
80-100	7.00	5	2.10	19.20	13.07	8	1.08	29.70

II: Mean thickness (cm) of salt-free top soils ($EC_e < 4$ mmhos/cm at 25°C)[2])

	inside	n[1])	outside	n[1])
A. Zebra kopjes	83	6	73	6
B. Gol kopjes enclosure	81	5	67	8

1) n: number of profiles

2) values for each profile estimated by inter- or extrapolation assuming linear trends of conductivities over the depths concerned.

between grassland and salinization types; it was, therefore, not allowed to draw conclusions on the basis of statistics. The following facts and tendencies may be observed.

- Near the Zebra kopjes and near the Gol kopjes enclosure, both inside and outside cages and enclosure, profiles that were salt-free down to a depth of 1 metre alternated with profiles that were strongly saline at a corresponding depth; near Zebra kopjes all profiles were moderately saline between 100 and 120 cm.
- Conductivities at corresponding depths for points inside the cages and exclosure tended to be lower than for points outside.
- The mean thickness of salt-free top soils - i.e. the layers in which EC_e values dis not exceed 4 mmhos/cm at 25° - inside the cages and the enclosure tended to exceed the corresponding values outside.

  The tendency for lower salt contents in the profiles inside the enclosure and the cages might be explained by assuming that the soils inside the cages and the enclosures are leached more intensively than those outside, which means that more rainwater will have to penetrate into the soil inside the cages than outside. The latter seems likely, because of the better permeability of the surface soil inside the fences: inside, the grasses have grown taller and cover the soil completely, thus preventing the surface soil from slaking by raindrops, whereas the soils outside the fences, being less protected against slaking as the vegetation consists of clumps of short grasses with a cover up to 40%, are marked by the presence of a thick surface crust ("surface capping"), which has a much lower permeability than the surface layer of the soils inside the fences.
- <u>Lime</u>

  As a result of the increase of the mean annual rainfall in this area a decalcification of the top soil has taken place. In correspondence with the rainfall gradient,the thickness of the decalcified top layer (e.g. lime percentages less than 1%) in ridge soils had increased from 0 in the SE to 30 cm in the west and north-west and north (see Fig. 35). In soils of flanks and especially in those of the valley bottoms, the decalcification had progressed to even greater depths due to the increased leaching effects by run-off and subsurface transport.

In the region between the Soguna and Zebra kopjes,calcic horizons were found at depths between 40 and 100 cm. Compared with situations in the Lemuta area (A.2) the calcic horizons had a greater thickness and higher lime percentages (see Table 12, and Appendices 11[1], 12[1] and 13).

Near the Gol kopjes a calcic horizon occurred at depths below 80-100 cm, which was comparable with situations in the Olduvai area (A.3).

Different patterns in the accumulation of lime were found in the erosion step areas: at bare spots, characterized by external salinization and a very high alkalinity, the surface soil contained several per cents of lime: precipitated from run-off and subsurface-transported moisture under highly alkaline conditions.

[1] available at the Dept. of Tropical Soil Science, Agricultural University, Wageningen, Holland.

2.1.5. Biological activity in the soil

a. Root development

In soils with a petrocalcic horizon at shallow depths (< 50 cm, soils units I.1.1.1, I.1.2.1), the soil layer above the petrocalcic horizon is rooted very intensively; roots form a mat on top of the petrocalcic horizon and only very few had penetrated further downwards through small holes or channels. A maximum accumulation was found in the top 15-20 cm; most were fine and medium roots; below 20 cm most roots were fine except for those of the herbs.
In soils with a petrocalcic horizon below 50 cm or without a petrocalcic horizon (soil units I.1.1.2 & 3, I.1.2.2, I.1.3.2) a similar root distribution was found till a depth of 40-50 cm; below this depth there was a marked decrease of the mass of roots coinciding with the upper zone of the salt-affected and (very) strongly alkaline part of the profile. Roots of salt tolerant grass species penetrated into the strongly saline (alkaline) parts of the profile

b. Dung beetles, termites and ants.

Dung beetles (coprid beetles) play an important rôle in these soils. During the wet season masses of dung are left on the soil surface by the hundred thousands of wild herbivores. (N.B. According to Waterhouse (1974) cattle in Australia were recorded to drop 12 dung pads per day). Almost immediately after the dung is dropped, the dung beetles start to dig themselves into the dung pad and to mix dung with the underlying soil material. Much of the dung is used for brood balls to serve as food for the larvae before hatching. The balls are dug into the soil by which vertical krotovina-like tunnels are formed in which the soil material had a fairly loose packing (SEK-NE). The soil structure became strongly disturbed during this process; the turning over of soil material did probably take place over short distances only, roughly 1 diameter of a ball (see also Waterhouse, 1974).

The sizes of the balls - depending very much on the (many) beetle species - was found to vary between a few mm and 10 cm; sizes between 5 and 7.5 cm were common. In the walls of a soil pit mostly broken balls or fragments (halfs) were found; in these cases the larvae had hatched and the beetles had dug their way out to the surface (through the same tunnel by which the dung ball had passed before?). The remains of the balls, left in the soil, consisted mostly of layered clayey soil material, since the dung had been eaten by the larvae.

The depths, to which the dung beetles had been dug or were found in the profile pits, were uncertain because of possible disturbance of their original position by termite activity.

The dung beetles definitely play a very important role in the recycling of the organic matter and nutrients. In the field loose, empty balls or even small collections of empty balls were often found; all had a hole of about 2-3 cm in diameter; these balls had been dug out by predators, mainly golden jackal (*Canis aureus*) hunting for the larvae.

c. Termites

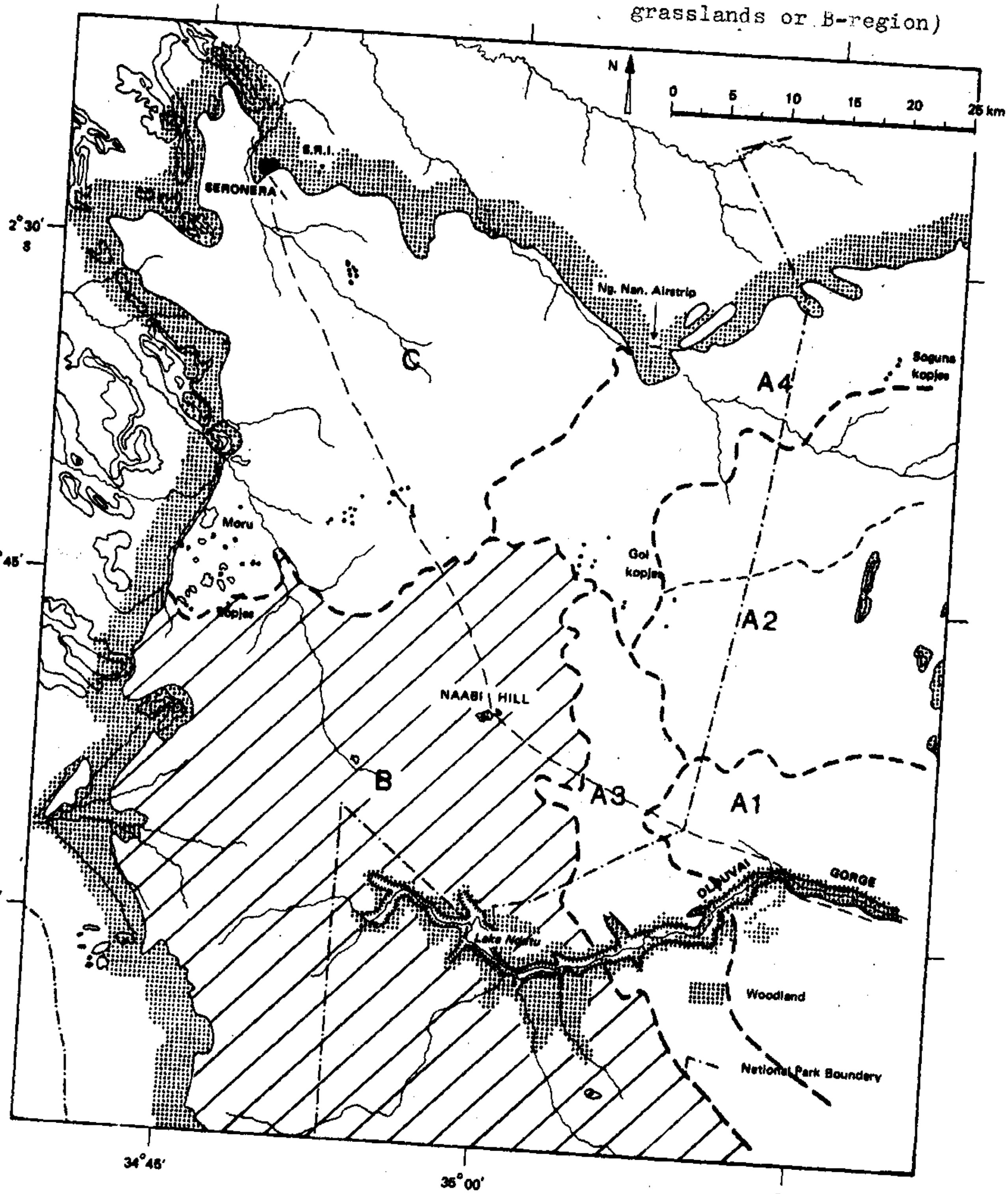
Termite activity could hardly be observed at the surface. In the soil profile globular nests that contained many small termites (up to 4-5 mm) were found at various depths. Although their size made them rather inconspicous, they appeared to be quite common. The soil pits described had been dug in the dry season and the only visible activity was the presence of the nests; but if the dry soil was moistened (e.g. for infiltration and bulk density measurements), the small termites came out immediately, even on a moistened spot at the surface. The water did also attract small yellowish ants (sizes up to 5 mm).

Contrary to the dung beetle activities, the effects of the termites on soil structure and the turning over of soil material (including salts!) could hardly be estimated; the effects, however, should not be underestimated.

d. Mammals

Mammals did also disturb the soil profiles, mainly by the digging of holes: hyena dens occurred in the deep soils of some valley bottoms, holes of honey badgers (*Mellivora capensis*) were often found in the walls of low scarps and waterholes; very common were small piles of soil material, thrown out by mice (species?). In all cases soil material, rich in salts, was brought to the soil surface in which way also mammals contributed - but on a small scale, in comparison with insects - to the recycling of minerals.

Fig 20: Location of soil landscape I.2 (*Andropogon greenwayi* grasslands or B-region)



2.2. Soils of the Angropogon greenwayi (Intermediate) grasslands

(soil landscape I.2 or B-region)

Loamy and clayey soils, mainly developed from volcanic ash with a moderate or strong horizon differentiation, locally saline or alkaline, with a non-calcareous top layer. The boundaries of the soil landscape have been outlined in Fig.20.

2.2.1. Soil characteristics

2.2.1.1. General description of the landscape, topography

Most striking characteristics of the landscape are the flat topography and the abundant occurrence of the grass species *Andropogon greenwayi* Napper in the floristic composition of the vegetation; the name *Andropogon greenwayi* grassland is used frequently as a synonym for soil landscape I.2.

The area studied lies west of the Short grasslands; in the north it is bounded by the Long grasslands, in the west by the Itonjo Hills and in the south by the Olduvai Gorge and its side arms. Striking features within the landscape are:

1. Naabi Hill, a gneissic outcrop of the Pre-Cambrian basement which belongs to the so-called Serengeti Group; it is covered by *Acacia*/*Commiphora* woodland; it is too big to be called a kopje, but too small to be a mountain.
2. Olduvai Gorge, the very deeply incised valley that drains into the Olbalbal depression in the east; the fairly steep walls of the valley are covered by *Acacia* woodland. South of Naabi Hill, where the valley bottom broadens, two soda lakes are found:

   Lake Ndutu (=L.Lagarja) and L.Masek; the larger L.Ndutu is shallow and very strongly saline/alkaline and may dry up in very dry years; the permanent L.Masek is less saline, probably as a result of the larger amounts of water of better quality, carried into the lake by some tributaries from the south.

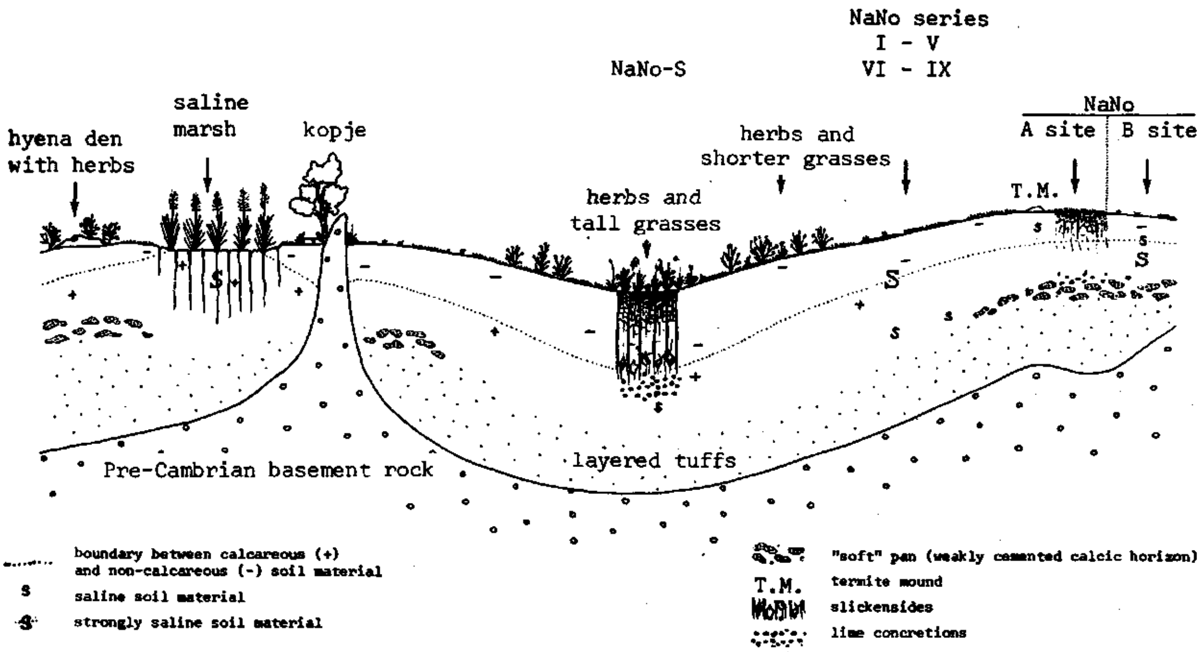
3. The Mbalageti valley, also called Hidden Valley, a deeply incised valley, especially near the origin, which strongly resembles the parts of the Olduvai Gorge west of L.Ndutu; on the valley bottom - which lies at the same level as that in the Old.Gorge! - two small,very shallow soda lakes are found: Ngorono and Kasciya.

Within the part of the Andropogon greenwayi grassland studied, Gerresheim (1974) distinguished 4 land system associations (14.25-14.28). The association 14.27 roughly coincides with a large flat area north, east and south-east of the Mbalageti valley, that is only little dissected and that borders on the Short grasslands. Across the area, south by Naabi Hill, runs the main water shed between the Lake Victoria and the Olduvai/Olbalbal catchment areas; it extends further southwards into the landsystem association 14.26. West and south-west of land system association 14.27, the area is more strongly dissected; the ridges however, are broad and flat.

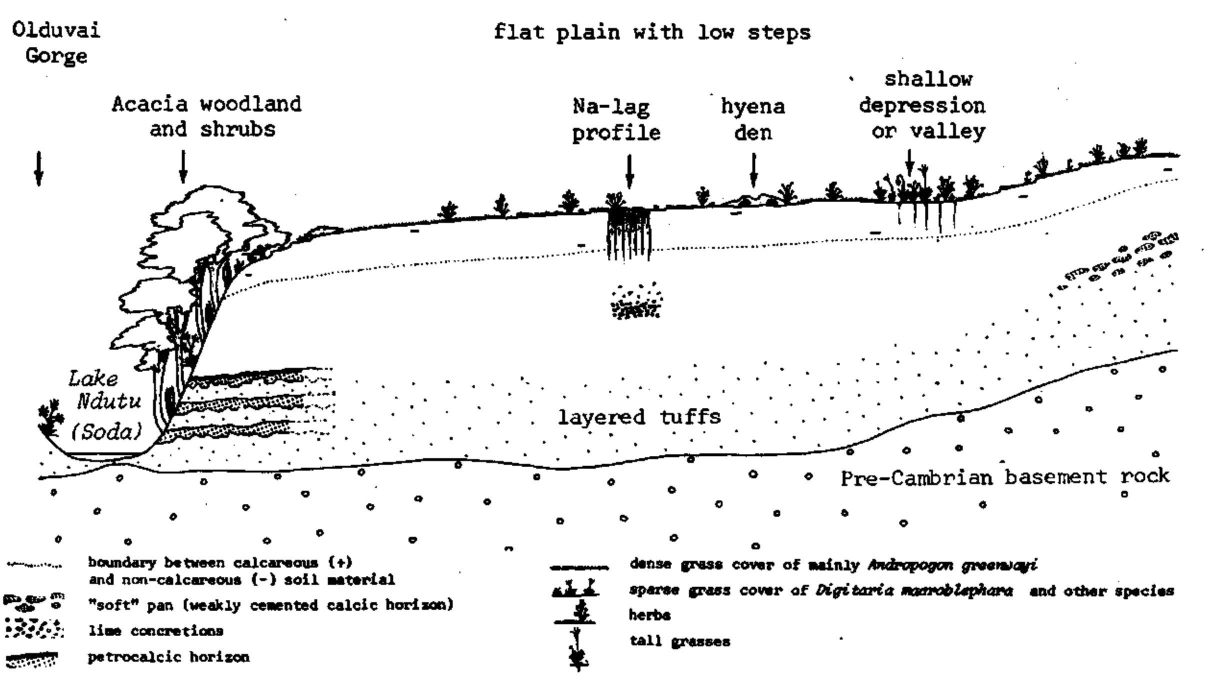
Apart from Naabi Hill, the Pre-Cambrian basement forms outcrops at a few places only. Most important are the so-called Hidden-Valley kopjes (granite) that are found on the west bank of the Mbalageti River near the boundary with the Long grasslands. Another more important group form the Soit O Ngum kopjes (also granite) that are located near the boundary between the Andropogon greenwayi grassland and the Simiyu area (Long grassland), south-east of Oldoinyo Olobaie. In the south-eastern half of the area, defined before as land system association 14.27, numerous low "steps" are found on the long very gently slopes; as they coincide with marked differences in vegetation,they show up very well on the aerial photographs; their orientation runs parallel with the contours. At some places, e.g. around Naabi Hill and on the more strongly sloping areas adjacent to the Olduvai Gorge, the steps resemble those in the Short grasslands (A.4 area!), but their heights seldom exceeded 20 cm; in other parts, east, south and south-west of Naabi-Hill,the heights were mostly less than 5-10 cm. In some places the steps were very low (few centimetres); their presence could be noticed, for

Fig.21: Soil landscape I.2 *(Andropogon greenwayi* grasslands).

a: Cross section through area north-west of Naabi Hill.



b: Cross section through area south of Naabi Hill.



instance, while driving a car up or down the slope ("bumpy" driving). Generally it has been noticed that the occurrence of steps was confined to the better drained parts of the Andropogon greenwayi grassland. Across the area, there was only a weak rainfall gradient: the mean annual rainfall varied from 650 mm in the east to 750 mm in the west.

Within the Andropogon greenwayi grassland various combinations of grass species have been distinguished; they were related with the "step" microrelief, with the relief position and drainage conditions (ridge, flank, valley bottom) or with activities by animals (termites and also larger mammals). Details will be discussed in Ch. 3 "special features" and in Part III: Vegetation and Soils. Besides the differences in drainage conditions, related with relief position within a catena, there were also regional differences: in the flat parts that form the watershed between the Simiyu drainage and that of the Mbalageti River, the soils are poorly drained and a few saline marshes do occur. In view of the different drainage conditions the latter area should have been discussed separately; the number of available data, however, was insufficient.

2.2.1.2. Morphology

Most of the data have been obtained from the eastern part of the Andropogon greenwayi grassland, north, east and south of Naabi Hill. Fig.21 shows a catena (A-B-C) based on descriptions of profiles NaNo-A and B (broad ridge), Na-Lag (flat plain) and NaNo-S (valley bottom), as well as on some other features that occur within this soil landscape; the profile descriptions have been given respectively in Appendices 16, 17 and 18 .

- Soil structure.

Although the above profiles were situated only 10 km west of the Short grasslands, the soil structure had become well developed in comparison with soils in the latter area. In the ridge and flat plain profiles (I.2.1.1) moderately weak to moderately strong, compound, coarse blocky or coarse prismatic structures where found which could be subdivided into (moderately) strong medium to very fine angular blocky elements in the top 20-25 cm, and into moderate coarse and medium porous blocky elements between 25 and 50 or 60 cm.

In the dry season cracks were found in the 0-60 cm top layer between the compound coarse structures; near the surface they were narrow but between 25 and 60 cm depth widths of 10-15 cm were recorded.

Soil colours in the top 50-60 cm varied between black near the surface to very dark grayish brown near the lower boundaries. The soil material below a depth of 50-60 cm showed great resemblance with that in the Short grasslands at corresponding depths; it was nearly structureless, it had a much lighter colour than the dark top soil and a high porosity; it was calcareous, and at some depth a strong accumulation of lime was found in the form of a dense layer of hard concretions, a weakly cemented pan or a combination of both. The boundary between the dark top soil and the light coloured subsoil was clear or gradual and slightly wavy.

Following the nomenclature to define soil horizons (Soil Survey Manual, 1962) the above profiles may be characterized as A(-B-)C profiles.

With respect to the above characteristics local differences, even over a short distance, were found:

- At the Nazu site, which lies only 1 km west of the Short grasslands, there was little differentiation in the moderate structural development in the dark top layer; in the lighter coloured subsoil below 80 cm loose very coarse concretions occurred that resembled pieces of petrocalcic horizon material of the Short grasslands. The Nazu profile was a typical AC profile.
- At the NaNo site there were differences in soil structure and other physico-chemical aspects between soils, that supported on almost pure stand of <u>Andropogon greenwayi</u> grassland, and those on which other grass species occurred (mosaics).

In the first case the grade of soil structure was stronger and there was a tendency towards a structural B-horizon: A(-B-)C profile. In the C-horizons of both profiles a so-called "soft pan" was found (at depths below 1 metre), consisting of clods and banks weakly cemented by lime, locally occurring as a nearly continuous phase. The "pan" material was essentially different from the petrocalcic horizons of the Short grassland soils because of its consistency. Anderson & Talbot (1965) refer to these soils as "calcimorphic soils with soft pan"; the term "soft pan" was used to distinguished these soils from those of the Short grasslands, which were called "calcimorphic soils with hard pan". The zone, in which the calcimorphic soils with soft pan occurred, formed a transition between the Short grassland soils and the more clayey soils in the western parts of the Plain that were defined as "Vertisols of lithomorphic origin" and "vertisols of lithomorphic origin in the south". Personal observations indicated that the distribution of the soils with a soft pan was bound to the ridge tops only, i.e. the best drained parts; most of them occur within the land system association 14.27 (Gerresheim, 1974). No "soft" pan was found in the soils of the flat plain south of Naabi Hill, which slopes very gradually down towards the Olduvai Gorge and the Mbalageti valley; instead of it, a layer largely consisting of very hard, almost indurated, irregularly shaped concretions was found.

No attempt was made to map the boundaries between the above variations. One exception, however, was made for soils that had a <u>petrocalcic horizon</u> (mostly within 1.20 metres). These soils occupied only a small area and appeared generally to coincide with areas in which trees - mainly <u>Acacia tortilis</u> - were found:

- Around Naabi Hill, in the upper parts of the pediments and in the colluvium at the very base of the hill.
- Areas adjacent tp the Olduvai Gorge and the Mbalageti valley, including the valley walls; these situations were similar to those in the eastern parts of the Olduvai Gorge and along the Magungu River and some other deeply incised valleys in the eastern Serengeti Plain. At Naabi Hill the petrocalcic horizon was found well exposed along the walls of an old gravel pit; hard layers with a vesicular structure alternated with layers of softer material. Fossilized bones of various mammals - a.o. rhinoceros, zebra, Thomson's gazelle, hyena and jackal - were found embedded in both the hard and the soft layers. Fossile bones have also been found on the west bank of Lake Ndutu; also ancient tools did occur, such as stone hand axes, which may date from the middle Pleistocene. Since both the bones and the tools have been washed out from petrocalcic layers, which outcrop abundantly along the valley walls and banks of the lake, they cannot provide useful information about the age of the various petrocalcic layers; studies of the fossiles in situ may give a clue.

Considering the nature of the petrocalcic material - which resembles dolomitic limestone, and differs from the material found in profiles in the eastern parts of the Serengeti Plain - and in view of the succession of layers of different grades of cementation and the presence of bones that were in an advanced stage of fossilization, the question may arise whether the occurrence of petrocalcic horizons in the above soils has been the result of recent soil forming processes or that they are related to former ash deposits.

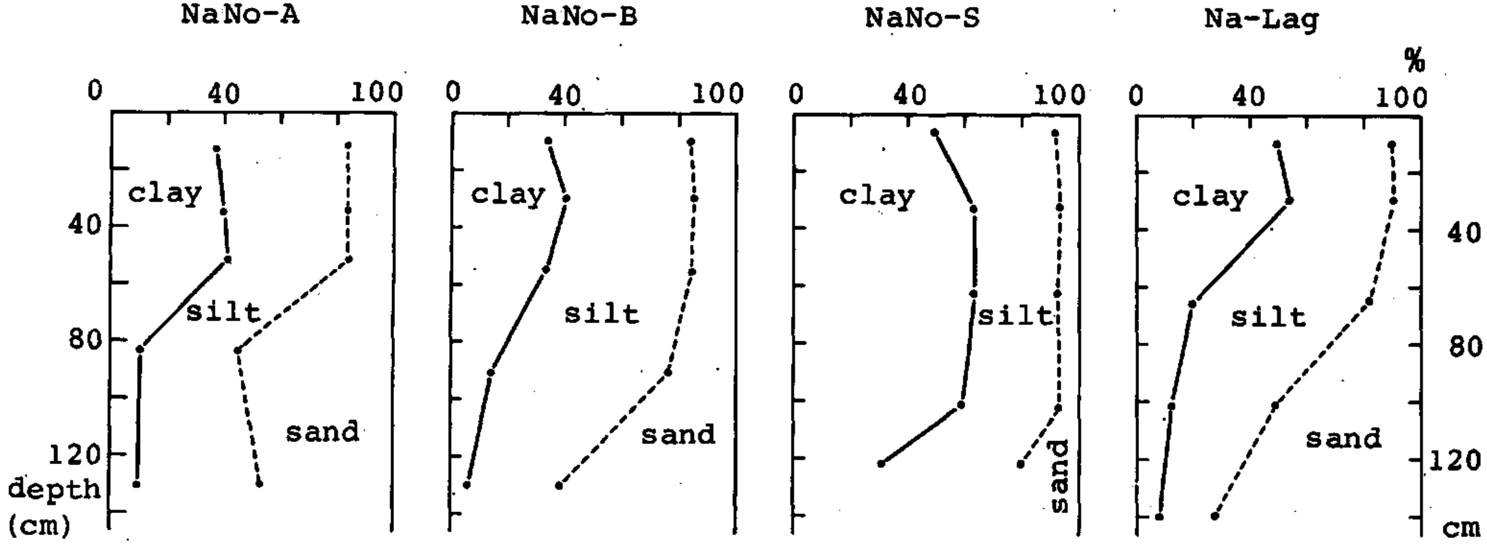
According to Anderson & Talbot (1965) tuffs blown from the Crater Highlands which had been deposited in lakes (L.Ndutu) have changed into a material that resembles limestone. It is not clear yet whether this "limestone" is similar to the petrocalcic material discussed before.

Only a few data of the soils of the flanks were available: NaNo-C and D , which were situated halfway the slope. From the collecting of soil samples from these soils it appeared that the thickness of the dark top layer had increased to 70 cm and - to judge from the resistance during augering - the soil structure had become more strongly developed compared with the ridge soils, especially between 20 and 70 cm, which might indicate the presence of a B-horizon (both structural and textural).

On the valley bottom the thickness of the very dark, nearly black top soil had increased to 1 metre or more. Near the surface a weak compound very coarse blocky structure was found, which fell apart into strong fine and very fine angular blocky non-porous elements when disturbed.
Downwards, the structure changed gradually into strong very coarse prismatic; the elements, separated by cracks up to 15 mm wide, were quite massive and at a depth of 1 metre they had been intersected by slickensides.
In view of the presence of cracks and slickness this soil can be classified as a vertisol.

In the area that extends west and south-west of the Mbalageti valley towards the Itonjo Hills and the Simiyu area, the grade of soil structure had become stronger. On the well drained ridges (HIVA-kopjes south-west, Old. Olobaie ridge), profiles were found that resembled the ones found halfway the flank south of the NaNo site: a thicker, dark top layer and a compacter consistency of the soil material.
In the less freely drained areas, which form part of the main water shed, cracks up to 5 cm wide have been recorded at the soil surface. These

Fig.22: Soil landscape I.2 (*Andropogon greenwayi* grasslands) : clay, silt and sand contents throughout 4 characteristic profiles; contents as percentages of the total mineral fractions (Oosterbeek method, see part I, Ch. 2: Methods).



NaNo-A: ridge top, 9 km north-west of Naabi Hill, *Andropogon greenwayi* spot
NaNo-B: ridge top, 9 km north-west of Naabi Hill, *Digitaria macroblephara* spot
NaNo-S: valley bottom, 7.5 km north-west of Naabi Hill
Na-Lag: flat plain, 6 km south of Naabi Hill

heavy-textured soils may be similar to those described by Anderson & Talbot (1965) as "Vertisols of lithomorphic origin". Considering the textural data, found for the latter soils (clay content of less than 30% occur in the upper 50 cm) by both authors, the classification as Vertisol seems incorrect. The better drained parts of the ridges in the west, which have developed from the same (volcanic) material as the soils at NaNo and Na-Lag, do certainly not belong to the "Brown calcareous soils" (Anderson & Talbot, 1965), whose distribution largely coincides with the boundaries of the Long grasslands in the north-western part of the Serengeti Plain and which were believed to have derived from a "calcareous conglomerate with little, if any ash addition".

2.2.1.3. Physical characteristics

- Soil texture, mineralogy

Fig.22 and Table 15 show the distribution of clay, silt and sand fractions throughout 4 profiles that were studied in detail. The figures for the separate fractions, the organic matter contents, the lime percentages and some other data have been listed in Appendix 19.

In the very dark top soils of the ridges and flat plain, the soil material could be classified as silty clay loam and silty clay, with a tendency of an increase of the clay contents between 20 and 50 cm. The lighter coloured, calcareous C-material (lime percentages higher than 1.0) had loamy textures; the boundaries between A and C horizons were fairly sharp (see profile descriptions). Coinciding with a sharp decrease of the clay percentage, and to a lesser extent also of the silt fraction, there was a strong increase of the sand fraction, especially of the fraction coarser than 300 μm in the Na-Lag and the NaNo-A profiles and also in the deepest layer of the NaNo-B profile.

The valley bottom profile (NaNo-S) was found to have a clayey texture throughout the dark top layer; between a depth of 13 and 40 cm there

Table 15: Soil landscape I.2 (Andropogon greenwayi grasslands): Soil texture

"Calcimorphic soil with soft-pan"[1]

depth (cm)	< 2 µm	2-50 µm	> 50 µm
0-15	28.1	38.4	33.5
15-45	18.8	35.0	46.2
45-65	12.3	34.3	53.4

"Vertisol of lithomorphic origin"[1]

depth (cm)	< 2 µm	2-50 µm	> 50 µm
0-12	30.7	31.6	37.7
12-30	32.3	35.2	32.5
30-60	13.0	32.0	55.0

NaNo-A[2]

depth (cm)	< 2 µm	2-50 µm	> 50 µm
0-25	37.8	47.1	15.1
25-45	40.1	44.7	15.2
45-57.5	41.8	43.6	14.6
70-95	10.8	35.0	54.2
120-140	10.1	43.4	46.5
0-25[3]	42.3	44.3	13.5

NaNo-B[2]

depth (cm)	< 2 µm	2-50 µm	> 50 µm
0-20	34.1	50.5	15.6
20-40	41.0	44.5	14.5
50-60	33.7	51.4	15.1
80-100	14.3	62.4	23.3
120-140	6.5	33.2	60.3
80-100[3]	23.6	64.6	11.9

Na-Lag[2]

depth (cm)	< 2 µm	2-50 µm	> 50 µm
0-20	49.7	40.7	9.6
20-37.5	54.4	36.8	8.8
55-75	19.5	62.8	17.7
95-110	12.5	35.6	51.9
130-150	6.6	20.8	72.6

NaNo-S[2]

depth (cm)	< 2 µm	2-50 µm	> 50 µm
0-13	50.0	42.6	7.4
26-40	62.9	31.2	5.9
55-70	63.1	29.9	7.0
90-114	59.2	33.3	7.5
114-130	30.7	49.4	19.9

1) Results given by Anderson & Talbot (1965); fractions as percentages of the totals of the mineral fraction (calculated); mechanical analysis was done by the hydrometer method using a mixture of sodium silicate and sodium hexametaphosphate as a disperging agent.

2) fractions as percentages of the totals of the mineral fractions; mechanical analysis acc. to methods used at Oosterbeek (see Methods): samples treated with N HCl to remove lime and sodium pyrophosphate to disperse.

3) samples treated with Na-EDTA, buffered at pH 5.0 - 6.0 by sodium acetate, in order to dissolve lime and to disperse the particles.

was a marked increase of the clay content; the C-material (below 114 cm) resembled the soil material in the upper parts of the C-horizons of the other profiles discussed.

Comparing the figures found for the "calcimorphic soils with soft pan" given by Anderson and Talbot (1965) for the dark top soils of the NaNo-A and B with those of the NaNo-A and B and the Na-lag profiles (Table 15) - the latter profiles were all situated within the zone of the "calcimorphic soils with soft pan" as marked by Anderson & Talbot (1965) - the clay contents in the calcimorphic soils were found to be much lower, the percentage of sand much higher. The same applies to the figures of the NaNo-S (valley bottom) profile and those of the "vertisol of lithomorphic origin", although clay contents in the latter profile were comparatively somewhat higher than in the calcimorphic soils with soft pan. The strong differences between the Oosterbeek figures and those given by Anderson & Talbot can be explained from the different methods used for the mechanical analysis (See Part I, Ch. 2: Methods).

The effect caused by different analysis procedures is shown by data obtained from NaNo-A (0-25 cm layer) and NaNo-B (80-100 cm layer) samples, which had been handled in a different way.

Between the NaNo-A 0-25 cm samples the differences in clay content was small, but in case of the highly calcareous NaNo-B 80-100 cm sample a considerably higher clay content was found when the sample was pre-treated with sodium-EDTA to dissolve the lime. This indicated that the latter sample contained an important percentage of amorphous material, and possibly also zeolites, that apparently did occur in the finest fraction only. By the pre-treatment with HCl, a part of the amorphous material and all zeolites (if any) became probably dissolved, which resulted into a lower clay percentage.

Table 16:

Soil landscape I.2 (*Andropogon greenwayi* grasslands): average bulk densities and soil moisture contents at various moisture tensions in a desiccating soil (NaNo, Na-Lag profiles)

depth, horizon (cm)	depth ring sample (cm)	(n)[1]	average[1]) bulk density (g/cm^3)	moisture contents (vol.%) at: pF1[2])	pF2[2])	pF4.2[3])	pF5.6[3])	SP[4])	COLE[5])
NaNo-A									
0-25	10-15	(4)	1.05	55.3	42.0	22.0	13.4	58.0	0.009
25-45	32.5-37.5	(4)	1.11	49.3	38.3	22.2	14.3	52.1	0.023
45-60/70	50-55	(4)	1.06	52.7	41.6	20.6	14.2	49.4	0.010
NaNo-B									
0-20	7.5-12.5	(4)	1.03	55.7	39.9	20.5	12.2	53.0	0.005
20-40	27.5-32.5	(5)	1.00	57.2	42.0	19.2	12.9	49.8	0.009
40-60	47.5-52.5	(4)	1.04	55.3	44.8	20.5	13.8	54.4	0.006
NaNo-S									
0-13	5-10	(10)	0.95	58.5	45.1	24.0	14.9	72.3	0.032
13-40	27.5-32.5	(7)	1.02	52.6	42.2	28.1	18.6	60.7	0.045
40-70	52.5-57.5	(4)	1.12	51.6	46.8	31.5	20.9	68.0	0.049
70-90	77.5-82.5	(5)	1.15	52.8	48.5	33.2	22.0	71.3	0.068
Na-Lag									
0-20	7.5-12.5	(5)	1.13	53.3	43.9	24.8	15.6	66.8	0.043
20-55	32.5-37.5	(6)	1.05	55.7	44.1	23.3	15.7	65.4	0.034
55-75	62.5-67.5	(4)	1.08	55.5	46.8	24.7	17.2	56.3	0.009

1) n = number of ringsamples per soil horizon; averages calculated from n measurements

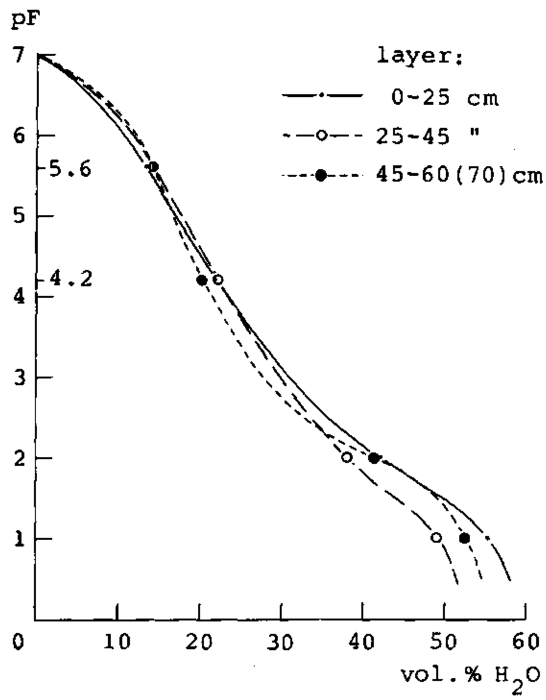
2) pF1 and pF2-values determined by measuring the weights of the ringsamples; averages calculated from n measurements

3) calculated from moisture contents (weight) of soil samples that had equilibrated with relative humidities of 98.8% (pF 4.2) and 75.8% (pF 5.6); see also Methods

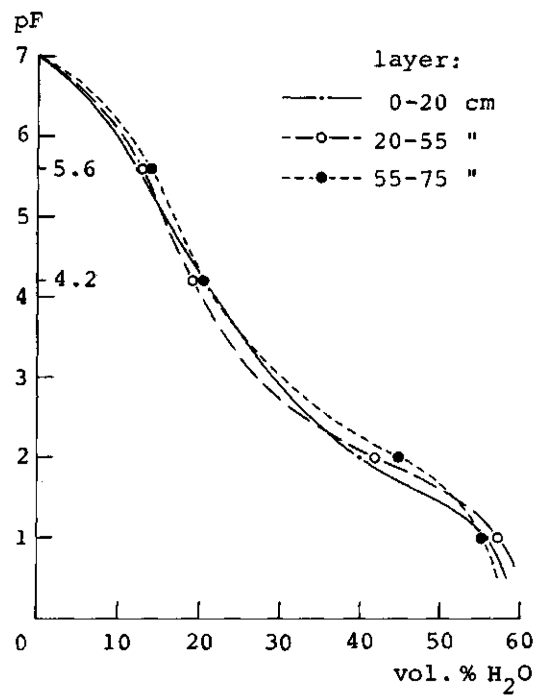
4) SP = Saturation Percentage of saturated soil paste (see Methods)

5) COLE: Coefficient Of Linear Extensibility: $\frac{Lm-Ld}{Ld}$ in which Lm = length of sample at 1/3 bar, Ld = length of sample when dry (Soil Taxonomy, 1975). COLE was estimated from the shrinkage of a ringsample at pF 2 (field capacity) that had been dried at 105 °C; COLE was assumed to be more or less equal for all directions throughout the undisturbed soil (see also Methods).

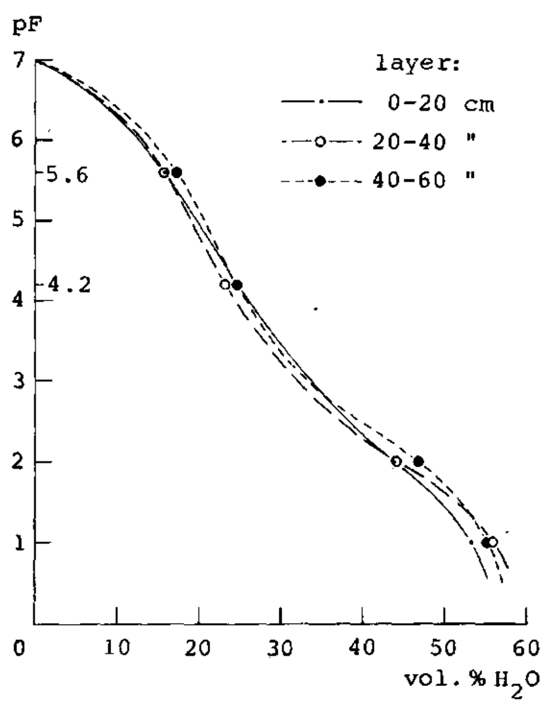
Fig.23: Soil landscape I.2 (*Andropogon greenwayi* grasslands): Moisture retention curves for various soil layers in 4 charateristic profiles.



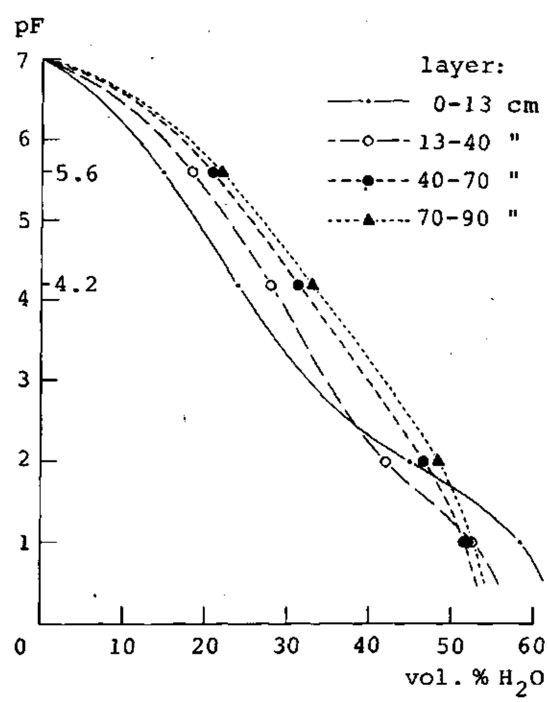
a: Na No-A (ridge top, 9 km N.W. of Naabi Hill, *Andropogon greenwayi*: spot).



b: Na No-B (ridge top, 9 km Naabi Hill; *Digitaria macroblephara* spot).



c: Na-Lag (flat plain, 6 km S. of Naabi Hill).



d: Na No-S (valley bottom, 7.5 km N.W. of Naabi Hill).

top soils of the <u>Andropogon greenwayi</u> grasslands but lower in those of the Long grasslands. The estimations of the humus contents by measuring the loss of weight on ignition ("Oosterbeek" method, results given in Appendices 19 and 34

are probably highly inaccurate - i.e. too high - because of the interference caused by the dehydration of amorphous materials or zeolites, which occur in substantial amounts in these soils; especially the figures obtained from C-horizon samples may suffer from this inaccuracy.

c. Base saturation in the epipedon area is over 50% throughout the study area: 100% in the eastern parts, gradually decreasing to 80% in the western and north-western parts.

d. Soil structures in the epipedons are not massive and hard or very hard when dry and the diameters of prisms or columns never exceed 30 cm.

e. Thickness of the epipedon is sufficient to be a mollic (eastern, central and western parts), or the surface horizon - after the soil is mixed to a depth of 18 cm - meets all requirements of a mollic epipedon except thickness, and the underlying soil (over 7.5 cm thick) forms part of an argillic or a natric horizon which meets all requirements of a mollic epipedon.

f. In most epipedons the amounts of phosphorus soluble in citric acid are less than 250 ppm; this excludes the epipedons from the Anthropic epipedon. For the cases in which the phosphorus contents exceed the limit of 250 ppm (e.g. GT III, NaNo-A), it would be difficult to identify them as Anthropic epipedons since these high contents are not the result of human activity in the past; the wolcanic ash itself appeared to be rich in anorganic phosphorus compounds (Apatite): Anderson and Talbot (1965) mention total P-contents up to 10.000 ppm in juvenile

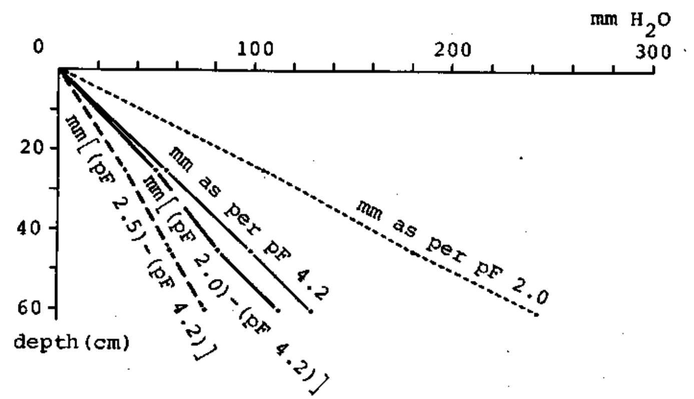
Table 17: Potential Wateravailability in 4 characteristic profiles in soil landscape I.2 (*Andropogon greenwayi* grasslands)

profile, depths (cm)		available moisture (mm)[1]			
		as per traject pF 2.0 - pF 4.2	average amounts (mm) per 10 cm layer	as per traject pF 2.5[2]-pF 4.2	average amounts (mm) per 10 cm layer
NaNo-A	0-25	50.0	20.0	34.5	13.8
	25-45	32.2	16.1	22.8	11.4
	45-60	31.5	21.0	18.6	12.4
	0-60	114.7	19.1	75.9	12.7
NaNo-B	0-20	38.8	19.4	26.4	13.2
	20-40	45.6	22.8	27.2	13.6
	40-60	48.6	24.3	31.6	15.8
	0-60	133.0	22.2	85.2	14.2
NaNo-S	0-13	27.4	21.1	17.9	13.8
	13-40	38.1	14.1	27.0	10.0
	40-70	45.9	15.3	36.0	12.0
	70-90	30.6	15.3	24.6	12.3
	0-90	142.0	15.8	105.5	11.7
Na-Lag	0-20	38.2	19.1	27.0	13.5
	20-55	72.8	20.8	47.3	13.5
	55-75	44.2	22.1	30.6	15.3
	0-75	155.2	20.7	104.9	14.0

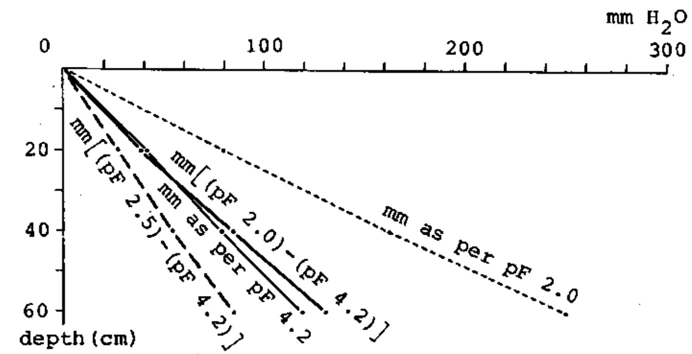
1) For the calculations the moisture contents at pF 2.0 and pF 2.5 (1/3 bar) were assumed to apply to the total thickness of the soil horizons distinguished.

2) Moisture contents at pF 2.5 estimated from the pF-curves.

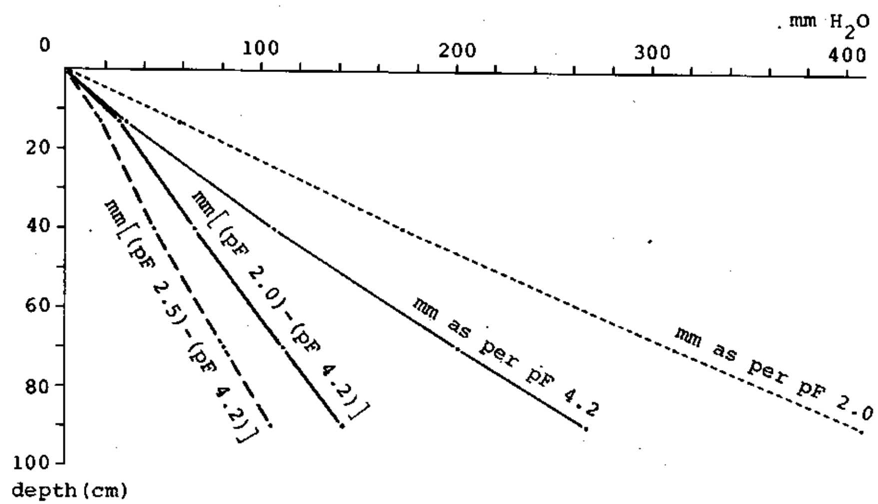
Fig.24: Soil landscape I.2: Amounts of soil moisture at pF 2.0 and pF 4.2 (mm) and amounts of available moisture (mm) accumulated with depth, for 4 characteristic soil profiles.



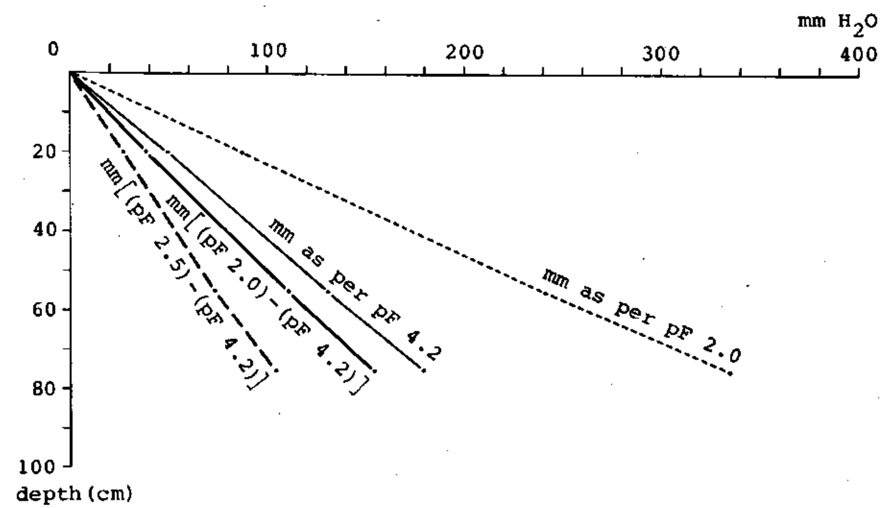
a: Na No-A (ridge top, *Andropogon greenwayi* spot).



b: Na No-B (ridge top, *Digitaria macroblephara* spot).



c: Na No-S (valley bottom).



d: Na-Lag (flat plain).

between the dark top soil and the C-material - remarkably small within each profile. The major difference in water retention between the above profiles and those in the eastern plain (I.1) are the much higher moisture contents at pF 2 and pF 1 (10-20 vol %) and the somewhat lower values at pF 4.2 and 5.6 found in the latter soils (Table 6a).

These differences had resulted in a considerably higher potential water availability in the eastern plain soils; average values of 40 mm per 10 cm versus about 20 mm based on the moisture traject between pF 2.0 and pF 4.2, and about 25 mm versus about 15 mm in case the traject between pF 2.5 (1/3 bar) and pF 4.2 was taken into account (See Tables 6b, 17). In the Na-Lag profile the moisture contents at pF 2.0, 4.2 and 5.6 had slightly increased compared with those in the NaNo-A and B profiles. From the surface soil (0-13 cm) of the NaNo-S profile (valley bottom), a pF curve was found that closely resembled the Na-Lag curves: soil texture of this layer was quite similar to that of the dark top soil of the Na-Lag profile. At lower depth (NaNo-S profile) the shape of the curves had changed into one which belongs typically to a heavy soil. The potential amount of available water below 13 cm have become even lower than the average values found for the other profiles, mainly as a result of the narrower availability trajects (higher moisture contents at pF 4.2 and 5.6, see Tables 16, 17).

The bulk densities of the dark top soils of the NaNo and Na-Lag profiles were higher than those at corresponding depths in the Short grassland soils, e.g. at BARSEK (see Table 6a). Contrary to the situation in the latter profile the bulk densities in the top soils - which were rich in organic matter - were equal or higher than values found for the C-horizon material, except for the NaNo-S surface soil. This fact indicates that the dark top soils - and especially the layers with a well-developed soil structure (NaNo-A 0-25 cm, NaNo-S 40-90 cm, Na-Lag 0-20 cm) - had considerably lower porosities than the soil material of the C-horizon, which may have consequences for the permeability of the top soils.

A comparison between the values obtained from the dark top soils of the NaNo and NaLag profiles on the one hand, and those found in the C-horizons of the same profiles as well as those found at the BARSEK on the other hand, was somewhat troubled by the shrinking of many of the ring samples from the profiles first mentioned after drying them at 105°C (Table 16); decreases of the original volumes (100 cm^3 at saturation as well as at moisture contents at pF 1 and pF 2) of over 20% did occur (Appendix 21[1]); see also COLE-values in Table 16).

- Infiltration

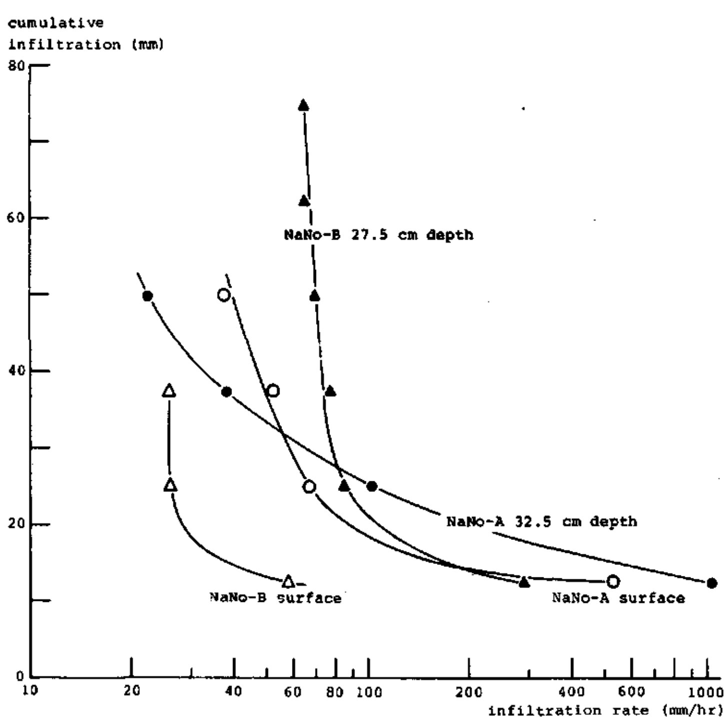
At the four sites studied, NaNo-A and B, NaNo-S and Na-Lag, infiltration experiments were done to estimate and compare the permeability and the capacity to absorb rainfall at various intensities at different depths. The mean infiltration rates, the lowest and highest values and the average number of mm infiltrated have been given in Appendix 22; most of the mean infiltration rates are shown graphically in Fig. 25.

The ways the infiltration experiments were carried out, are discussed in Part I, Ch. 2: Methods.

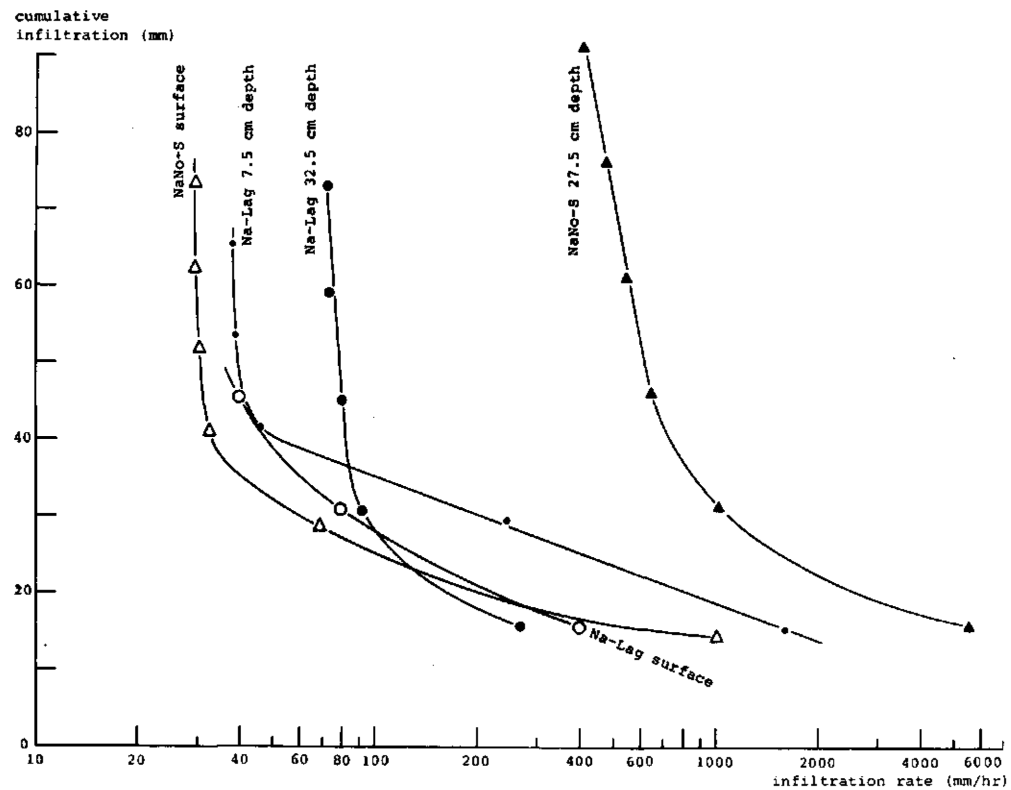
Infiltration rates were found to be very high in the dry soils (Experiment I); in the dry NaNo-B surface soil permeability was markedly low; in the NaNo-S profile at a depth of 27.5 cm, it was extremely high. During the continuation of the infiltration experiments (II, III, etc.) which succeeded each other without interruption, the permeabilities tended to

[1] available at the Dept. of Tropical Soil Science, Agricultural University, Wageningen, Holland.

Fig.25: Soil landscape I.2 (*Andropogon greenwayi* grasslands): Mean infiltration rates as related to total amounts of millimetres water infiltrated, for 4 characteristic profiles, measured at various depths; infiltration rings pushed into the soil by car jack.



a: Na No-A (ridge top, 9 km north-west of Naabi Hill, *Andropogon greenwayi* spot) and Na No-B (*Digitaria macroblephara* spot, adjacent to Na No-A site).



b: Na No-S (valley bottom, 1.5 km south of Na No-A and B sites) and Na-Lag (flat plain, 6 km south of Naabi Hill).

stabilize (infiltration under saturated conditions) at considerably lower values, that were reached after a more or less gradual decrease.
A constant infiltration rate was reached first in the NaNo-B surface layer, which was most certainly caused by the presence of a surface crust - which had originated by slaking - and a stable soil structure and porosity.
Slaking of the NaNo-B surface soil was favoured by the comparatively low soil coverage percentage of the grass vegetation; the effect of surface capping on permeability was already found in the Short grasslands (I.1). The surface crust effect did not occur at the NaNo-A, NaNo-S and Na-Lag sites where the vegetation covered the soil for nearly 100%.The high infiltration rates in the above surface soils - in particular when dry - have to be attributed to the presence of numerous cracks between the soil aggregates and also to the common occurrence of variously sized biopores. During the continued infiltration the infiltration rates decreased as a result of the swelling and partial disintegration of the wetted aggregates by which, moreover, the larger cracks and biopores became filled up. The decrease of permeability did especially occur in those soil layers in which fine soil aggregates and fine cracks predominated (NaNo-A surface and 32.5 cm level, Na-Lag surface, NaNo-S surface).
In soil horizons,in which coarse and structural elements were dominant, the above effects were less important since most of the water did probably drain off through the larger cracks (NaNo-S,27.5 cm level); the high clay contents in the NaNo-S profile below 26 also contributed to a higher stability. The permeability of the soil material within a coarse structural element appeared to be low: a value of 4.7 mm/h was measured in the NaNo-S profile at 52.5 cm depth. For several reasons the measured infiltration rates, namely for surface soils, may be too high:

1. During the procedures of pushing the infiltration rings into the soil the number of cracks may have increased, which may have resulted into too high infiltration rates, especially in a crusty surface soil (NaNo-B surface, NaNo-S surface).
2. Due to the way the infiltration experiments were carried out. The swelling of the aggregates during infiltration might not have exerted its maximum effect on the permeability; intermittent experiments, using the same number of millimeters, would have left more time for the aggregates to swell, which might have resulted in lower permeabilities than the ones given in App. 22. Also the potential swelling of the surrounding soil (e.g. during rainfall) has not been taken into account.
3. The way the mean infiltration rates have been calculated (see Methods) did also result into too high values (for experiments III or one of the following).

The infiltration characteristics shown in Fig.25 give also some information about the capacities of the various soil layers to absorb a certain amount of rainfall at various intensities or ,oppositely, various amounts of rainfall of a certain intensity.
In this part of East Africa cumulative amounts of rainfall of 10-20 mm or more at intensities of 30 mm/hr or more are quite common (Taylor and Lawes, 1971). This means, for example, that at sites like NaNo-B run-off may occur frequently, especially if such sites are in a slightly elevated position or in case they are found on the flanks. Both situations occurred abundantly in the eastern and central parts of the <u>Andropogon greenwayi</u> grasslands; they could immediately be identified from the vegetation mosaics.

The run-off, that may come from sites like NaNo-B, can be expected to be absorbed for the greater part in the soils that had properties similar to those at NaNo-A (NaNo-A and B formed mosaics). During prolonged heavy rainfall this did result (personal observation) into a situation in which sites like NaNo-B remained relatively dry and those like NaNo-A became soaked.

The run-off effects, caused by the impeded drainage in the surface crust, can also be expected to increase towards the valley bottom. Under prolonged wet conditions, the valley bottom soils (NaNo-S) become therefore rapidly water-logged because even the larger cracks will close by swelling of the larger structural elements. The low permeability of the heavy clay and dense soil will then act as a nearly impermeable layer: e.g. in the NaNo-S profile below 40-70 cm. It may be clear that the large differences in internal drainage between the soils discussed must have, or must have had effects on physical and chemical properties of these soils.
Especially with respect to the chemical properties, namely salinity, there was ample evidence for this.

2.2.1.4. Chemical characteristics

- Salinity and alkalinity

The sampling of profiles to study chemical properties of the soils of the *Andropogon greenwayi* grasslands (soil landscape I.2) was carried out in close connection with the vegetation patterns distinguished. At 11 of 14 sites investigated - of which 10 were situated on ridges and in the flat plain - vegetational mosaics were found which consisted of:

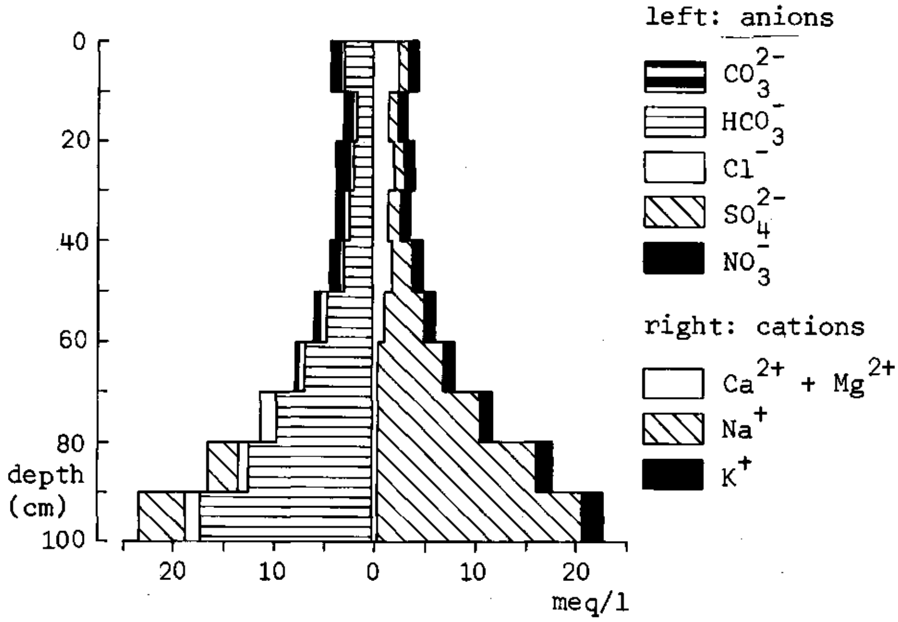
- sharply bound patches of almost pure stands of *Andropogon greenwayi*, which covered the soil for nearly 100 percent and constituted 50% or more of the total vegetation cover
- patches of a more open grass vegetation with *Digitaria macroblephara*, *Pennisetum stramineum* and *Cycodon dactylon* as dominant species; often with short physiognomy.

In the mosaics, the profiles to be sampled were selected in adjacent spots of different botanical composition: the profiles, located in the *Andropogon* patches, have generally been indicated as A-profiles, the ones in the more open grass vegetation as B-profiles. At the Golzu-site (near Gol kopjes) and around and inside the Naabi south-east enclosure (just east of Naabi Hill) several replicates of A and B-profiles were made.
At the NaNo-site (10 km north-west of Naabi Hill) two transects have been sampled across an *Andropogon greenwayi* spot and an adjoining spot without *Andropogon greenwayi*: NaNo I-V and NaNo VI-IX. In both transects a low termite mound was included because termite activity was supposed to have considerable effects on the chemical status of the soils, and possibly - indirectly - also on the origin of the grassland mosaics within the *Andropogon* grasslands.

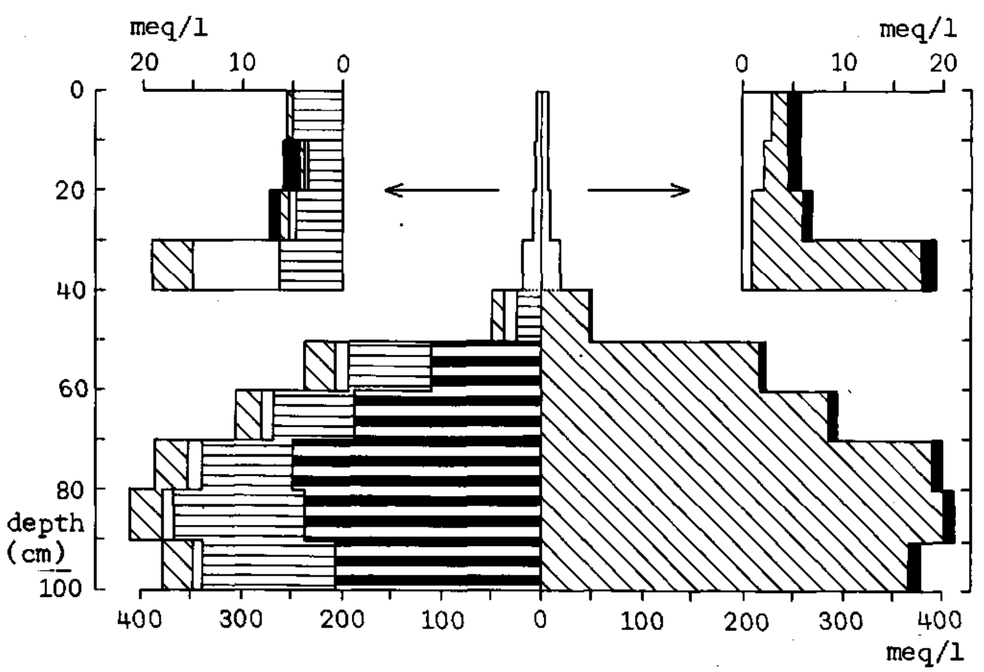
Within the Andropogon greenwayi grasslands (soil landscape I.2) both internal and external salinization were found.
Soils, that were internally salt-affected within the upper 100-120 cm, were found in the eastern and north-eastern part of the Andropogon greenwayi grasslands and appeared to be associated with the more open grassland types: B-profiles.
These profiles were strongly saline below 50 cm and also very strongly alkaline (pH-values of the saturates pastes of over 10.0), due to the presence of considerable amounts of soluble carbonates and bicarbonates. The sites concerned were Golzu I (Fig.26 ; App. 23) and II (App.24[1]), NaNae 3 (Table 18) and NaNo-B (Fig.27 ; Table 19).
Under the Andropogon greenwayi stands at the same sites (A-profiles), the soils were non-saline to a depth of 1 metre, and much less alkaline than the B-profiles, also below 1 metre (pH-values rarely exceeding 9.0). At the Nazu-site (Appendix 25[1]), where an almost pure stand of Andropogon greenwayi occurred, a different situation was found: the soil was moderately saline and very strongly alkaline below 70 cm. Since the soil samples had been collected from a soil pit that had been open for over half a year, it is not clear whether this situation was representative for the surrounding area.
Around the Naabi south-east enclosure (Appendix 26[1]) - which is situated at the base of Naabi Hill - neither the A nor the B-profiles were saline within the upper 120 cm; the greater thickness of the non-saline top soil, namely in the B-profiles, may be related with the site's topographic position and the consequently stronger effects of leaching (run-off!) in this place.

The profiles in the central and western parts of the Andropogon greenwayi grasslands (Na-Lag; Hiva-A, B; Hivak-A, B; Old. Olobaie A,B) - all of them were situated on the flat plain or on broad, flat ridges - were non-saline to a depth of 120 cm and slightly acid in the top

Fig.26: Salinity patterns and salt composition in 2 profiles of the flat plain within soil landscape I.2 near the Gol kopjes; ion concentrations in milliequivalents per litre of the saturation extracts.



a: Golzu-A (flat plain, *Andropogon greenwayi* spot).



b: Golzu-B (*Digitaria macroblephara* spot).

Table 18 : salinity figures and CEC, ESP etc.

<u>NaNae 3 Agre</u>

Depth (cm)	SP	pH_p	pH_e	EC_e	Na^+	K^+	Ca^{2+}	$Ca+Mg^{2+}$	sum^+(me/L)	$CO_3^{2-} + HCO_3^-$	Cl^-	SO_4^{2-}	sum -	% lime
0-20	61.6	6.68	7.95	0.81	1.17	1.94	4.51	5.96	9.07	5.27	0.40	0.34	6.01	0.34
20-40	57.9	6.78	7.94	0.49	1.37	1.15	2.41	3.00	5.50	2.81	0.18	0.23	3.22	0.31
40-60	59.4	7.30	8.39	0.63	3.02	1.10	2.37	2.76	6.88	4.28	0.17	0.21	4.66	1.01
60-80	52.6	7.76	8.60	0.69	5.13	1.06	1.15	1.29	7.48	4.59	0.25	0.72	5.56	3.49
80-100	46.0	7.93	8.73	0.88	7.52	1.19	0.81	1.01	9.72	6.02	1.20	1.08	8.30	4.88

<u>NaNae 3 Cyda</u>

Depth (cm)	SP	pH_p	pH_e	EC_e	Na^+	K^+	Ca^{2+}	$Ca+Mg^{2+}$	sum^+(me/L)	$CO_3^{2-} + HCO_3^-$	Cl^-	SO_4^{2-}	sum -	% lime
0-20	50.3	7.00	8.17	0.69	1.56	1.16	3.31	4.01	6.73	4.93				0.44
20-40	49.6	7.61	8.56	1.11	9.15	0.63	1.49	1.65	11.43	5.41				0.80
40-60	-	8.27	8.73	4.71	45.43	1.13	1.73	1.95	48.51	7.91				3.12
60-80	48.4	8.90	9.11	5.32	55.22	1.35		1.41	57.98	14.94				6.93
80-100	45.9	9.65	9.75	8.70	103.70	2.52		-	106.22	43.84				9.75

<u>NaNae 3 Agre</u>

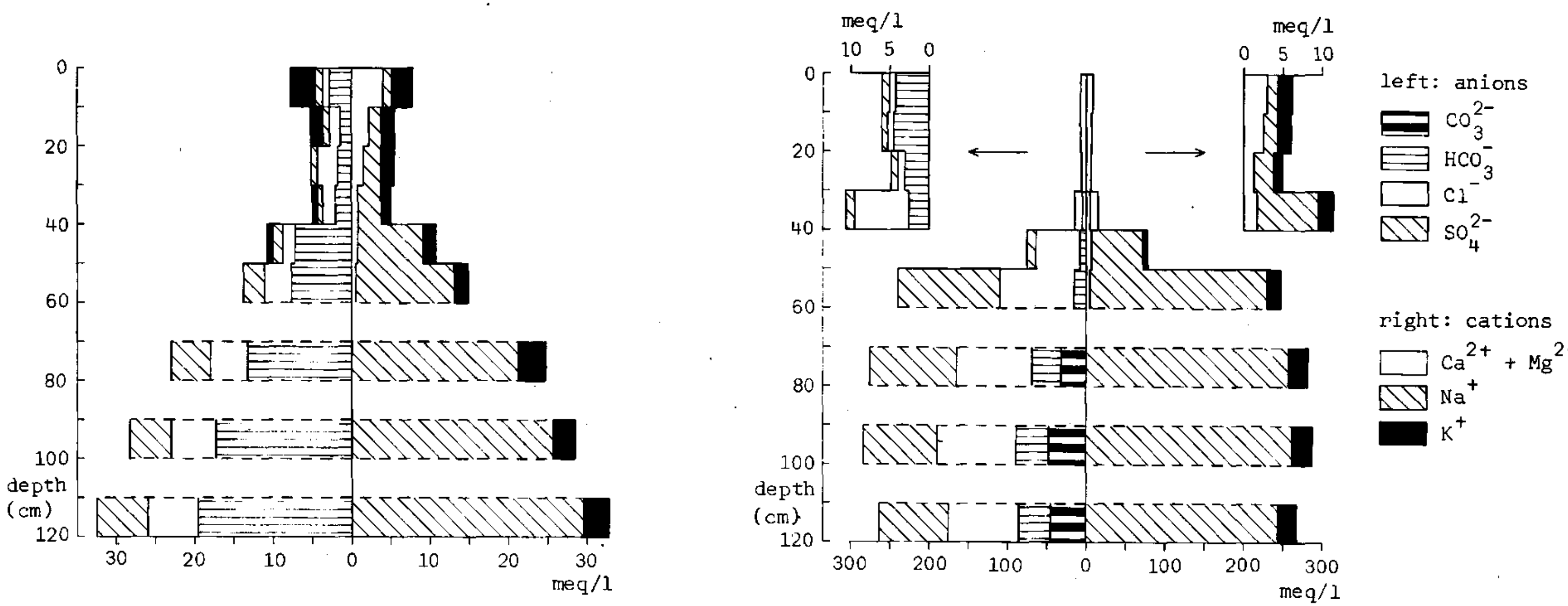
CEC, ESP etc (corrected) in meq/100 g.

	CEC	Na^+	K^+	Ca^{2+}	Mg^{2+}	T.B.	H^+
0-20	40.21	0.55	7.39	26.23	5.66	39.83	0.38
40-60	41.30	1.46	6.45	29.45	5.04	42.40	
80-100	40.76	5.80	11.03	22.63	6.43	45.89	

<u>Percentages:</u>

	CEC meq/100 g	% Na	% K	% Ca	% Mg	B.S.	% H
0-20	40.21	1.37	18.38	65.23	14.08	99.06	0.94
40-60	42.40	3.44	15.21	69.46	11.89	100.00	-
80-100	45.89	12.44	24.04	49.31	14.01	100.00	-

Fig.27: Salinity patterns and salt composition in 2 ridge top profiles within soil landscape I.2; ion concentrations in milliequivalents per litre of the saturation extracts.



a: Na No-A (ridge top, *Andropogon greenwayi* spot).

b: Na No-B (ridge top, *Digitaria macroblephara* spot).

Table 19. Chemical data NaNo-sequence (soil landscape I.2 *Andropogon greenwayi* grasslands)

NaNo-A (*Andropogon greenwayi* spot)

depth (cm)	SP	pH_p	pH_e	EC_e	Na^+	K^+	$Ca+Mg^{2+}$	Sum +	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Sum -	%Lime
					all in meq/l of the sat.extracts										
0– 10	62.4	6.62	7.39	0.89	1.15	2.65	4.14	7.94	-	2.75	0.93	1.04	3.00	7.72	0.39
10– 20	58.0	6.51	7.93	0.60	1.48	1.73	2.27	5.48	-	1.34	1.53	0.96	1.50	5.33	0.31
20– 30	53.6	6.52	8.01	0.58	2.20	1.66	1.56	5.42	-	1.82	2.60	1.00	<0.25	5.42	0.45
30– 40	52.1	6.69	8.24	0.53	3.22	1.19	0.54	4.95	-	2.06	1.60	0.77	0.50	4.93	0.29
40– 50	54.2	7.45	8.79	1.05	8.61	1.67	0.54	10.82	-	7.32	1.53	1.20	0.50	10.55	0.38
50– 60	49.4	8.11	8.94	1.43	12.87	1.84	0.20	14.91	-	7.58	3.50	2.47	<0.25	13.80	2.89
70– 80	45.0	8.72		2.30	21.39	3.28	1)	24.67	-	13.25	4.80	5.00	-	23.05	6.75
90–100	42.2	9.06		2.80	25.57	2.84	-	28.41	-2)	17.32	5.70	5.10	-	28.12	16.37
110–120	40.7	9.11		3.25	29.74	3.10	-	32.84	-	19.59	6.40	6.50	-	32.49	16.22

1) not determined, pH >8.5
2) water acid !

NaNo-B (*Digitaria macroblephara* spot)

depth (cm)	SP	pH_p	pH_e	EC_e	Na^+	K^+	$Ca+Mg^{2+}$	Sum +	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Sum -	%Lime
0– 10	53.1	6.73	8.20	0.59	1.13	1.89	3.06	6.08	-	4.23	0.79	0.61	-	5.63	0.31
10– 20	52.8	6.81	8.10	0.57	1.57	1.76	2.65	5.98	-	4.41	0.66	0.55	-	5.62	0.24
20– 30	48.6	6.96		0.48	2.37	1.07	1.43	4.87	-	2.98	1.06	0.71	-	4.75	0.26
30– 40	51.1	7.18		1.12	8.04	1.76	1.53	11.33	-	2.78	6.87	0.82	-	10.47	0.08
40– 50	55.7	7.79	8.33	7.90	64.78	6.35	5.71	76.84	-	3.40	58.74	12.04	-	74.18	0.72
50– 60	53.0	8.90	8.96	21.10	226.96	17.95	2.65	247.56	-	11.00	100.61	126.11	-	237.72	2.87
70– 80	48.8	9.70	9.74	23.10	258.26	23.63	-	281.89	31.44	36.64	96.87	109.55	-	274.50	7.82
90–100	43.8	9.80	9.84	23.80	262.17	25.47	-	287.64	45.80	40.60	101.31	93.63	0.75	282.09	22.10
110–120	42.2	9.81	9.84	22.10	246.52	22.40	-	268.92	44.14	41.74	89.39	85.99	0.50	261.76	15.62

NaNo-Fl.-A (flank. *Andropogon greenwayi*: spot)

depth (cm)	SP	pH_p	pH_e	EC_e	Na^+	K^+	$Ca+Mg^{2+}$	Sum +	CO_3^{2-}	HCO_3^-
0– 20	58.7	6.39	8.06	0.38	0.67	1.24	1.79	3.70		2.01
20– 40	58.3	6.38	8.11	0.23	0.53	0.64	0.94	2.11		1.04
40– 60	62.8	6.63	8.05	0.18	0.50	0.45	0.81	1.76		0.97
60– 80	52.7	7.21	8.36	0.40	1.17	0.70	1.62	3.49		3.46
80–100	51.3	7.43	8.51	0.43	1.69	0.67	2.19	4.55		3.25

NaNo-Fl.-B (flank, sparse cover with *Digitaria macroblephara* etc.)

depth (cm)	SP	pH_p	pH_e	EC_e	Na^+	K^+	$Ca+Mg^{2+}$	Sum +	CO_3^{2-}	HCO_3^-
0– 20	51.4	6.74	8.24	0.57	1.07	1.55	2.53	5.15		
20– 40	53.9	7.00	8.21	0.42	2.03	0.68	1.21	3.92		1.49
40– 60	52.7	7.47	8.54	0.64	4.43	0.60	1.15	6.18		2.14
60– 80	63.4	7.58	8.50	0.80	5.74	0.68	1.28	7.70		3.35
80–100	56.6	7.85	8.62	1.01	7.57	0.86	1.28	9.71		3.18

Table 20 : chemical data NaNo-S and Na-Lag profiles

profile depth (cm)	SP	pH_p	pH_e	EC_e	Na^+	K^+	$Ca + Mg^{2+}$	Σ^+	$H CO_3^-$	Cl^-	SO_4^{2}	NO_3^-	% Lime
					all concentrations in meq/1 of the saturation extract								
NaNo-S													
0- 13	72.3	6.80	8.24	0.52	0.72	1.35	3.58	5.65	4.18			-	0.40
13- 26	65.1	6.43	8.12	0.24	0.53	0.57	1.21	2.31	1.18			-	0.23
26- 40	60.7	6.37	7.91	0.23	0.58	0.43	1.28	2.29	1.18			-	0.23
40- 55	61.2	6.40	7.96	0.19	0.63	0.31	0.91	1.85	0.87			0.50	0.44
55- 70	74.7	6.65	8.17	0.23	1.03	0.26	1.08	2.37	1.46			-	0.21
70- 90	71.3	6.75	8.01	0.19	1.10	0.19	0.71	2.00	1.05			0.25	0.32
90-114	68.1	7.04	8.26	0.26	1.67	0.19	0.81	2.67	1.81			0.10	0.27
114-130	65.9	7.42	8.59	0.41	2.39	0.26	1.69	4.34	3.34			-	5.98

Na-Lag	SP	pH_p	pH_e	EC_e	Na^+	K^+	$Ca + Mg^{2+}$	Σ^+	$H CO_3^-$	Cl^-	SO_4^{2}	NO_3^-	% Lime
0- 10	66.0	6.40	8.06	0.45	0.73	1.17	2.70	4.60	2.75	0.63	0.46		0.39
10- 20	67.5	6.40	8.10	0.34	0.81	0.88	1.69	3.38	2.34	0.31	0.34		0.09
20- 37,5	65.4	6.52	8.14	0.31	0.84	0.74	1.52	3.10	1.72	0.25	0.28		0.20
37,5- 55	63.3	6.88	8.10	0.32	1.33	0.60	1.42	3.35	1.44	0.25	0.34		0.02
55- 75	56.3	7.50	8.65	0.50	3.43	0.65	1.42	5.50	3.96	0.37	0.29		1.05
75- 95	48.0	7.89	8.89	0.83	7.74	0.53	0.81	9.08	6.09	0.37			3.56
95-110	46.2	8.33	8.99	1.27	13.09	0.54	0.41	14.04	9.50	0.37	1.33		4.84
110-130	43.5	8.63	9.18	1.60	16.61	0.63	1.01	18.25	13.44	0.56	2.06		8.18
130-150	43.3	8.82	9.23	2.08	21.91	0.59	0.68	23.18	15.09	0.65	3.58		5.83

<u>Na-Lag</u>: exchangeable cations, cation exchange capacity (meq/100 g of soil)

	CEC	Na	% of TB	K	% of TB	Ca + Mg	% of TB	Total Bases	Base Sat.
0- 20	40.76	0.64	1.65	5.91	15.25	32.20	83.10	38.75	95.07
20- 55	40.22	0.90	2.17	5.41	13.06	35.12	84.77	41.43	100.00
55- 75	40.62	2.31	5.27	5.66	12.91	35.88	81.82	43.85	100.00
75 - 95	37.91	7.17	16.79	6.12	14.33	29.41	68.88	42.70	100.00

layer to moderately alkaline at lower depth (Table 20, App. 27[1] and 28). The conductivities of the saturation extracts (EC_e) and the pH-values of the saturated soil pastes (pH_p) were consistently lower under <u>Andropogon greenwayi</u> grassland (A-profiles).

From the gradual increase of the EC_e and the pH_p-values with the depth one might conclude that saline/alkaline soil layers may occur in the above profiles below a depth of 120 cm. Salinity and alkalinity patterns for the A and B-profiles at the NaNo flank-site (Table 19) were very similar to those of the A and B-profiles in the central and western parts just mentioned; the lower EC_e and pH-values were found again under the <u>Andropogon greenwayi</u> grassland.

Lowest conductivities and pH-values were found in the NaNo-S (valley bottom) profile (Table 20).

The decrease of EC_e and pH-values from the ridge (NaNo A, B) towards the valley bottom (NaNo-S) illustrates the increased effects of leaching caused by the higher mean annual rainfall in this area (when compared,for instance with situation in the eastern parts of the short grasslands).

External salinization was recorded in a few places only. Most of these places were poorly drained or, at least, temporarily poorly drained, e.g. 4 km east of Oldoinyo Olobaie and around the so-called Hidden Valley kopjes. The salt-tolerant grass species <u>Sporobolus spicatus</u> was very common in these places. An interesting aspect in the salt affected area near Old. Olobaie was the presence of low scarps (up to 30 cm high); they closely resembled the erosion steps of the Short grasslands, and their occurrence seemed to be bound to the strongly salt-affected soils only. Other areas affected by external salinization were the saline marshes and the bottoms of some deeply incised valleys (Mbalageti River, Olduvai Gorge); they have been included in the Miscellaneous land types.

- Salt composition

In the top 30-40 cm of the non-saline soils and in the non-saline topsoils of the internally salt-affected soils, soluble Ca, Mg and K constituted more than 50 per cent of the totals of cations.
At lower depth, and with increasing EC_e-values - especially in the B-profiles, which supported a sparse cover of grasses other than Andropogon greenwayi -, soluble Na became rapidly the dominant cation.
In the moderately and strongly saline subsoils of the B-profiles at the Golzu, NaNae and NaNo-sites, the solubility of Ca and Mg ions had become negligibly low as a result of the high pH; soluble K was an important component amounting up to 10 per cent of the totals of cations.
Bicarbonate was the dominant anion in the non-saline parts of the soil profiles (except for the NaNo flank - B profile). In the strongly saline subsoils of the Golzu I-B, II-B, NaNae 3-B and Nazu profiles, carbonate plus bicarbonate amounted 50 per cent or more of the sum of cations (Golzu I-B!). In the upper part of the saline subsoils chloride concentrations were relatively high; in the NaNo-B profile (40-50 cm) chloride was even the dominant anion.
The relative accumulation of chloride in the upper part of the saline zone within a soil profile has already been described for various soils of the short grasslands.
Nitrate was found in several profiles at varying depth and in varying concentrations.
At the NaNo-site (NaNo I-V and NaNo VI-IX series) high nitrate concentrations were found in samples collected from termite mounds.
Special attention to the accumulation of nitrate in termite mounds has been paid in Ch. 3 : Special features.

Although the total number of profiles investigated was limited, the following tendencies may be noticed:

- the amounts of soluble K - as a percentage of the totals of cations - seem to increase from the east to the west. Especially high K-contents were found in the Oldoinyo Olobaie profiles.
- carbonate plus bicarbonate contents in the strongly saline subsoils (B-profiles) seem relatively higher near the boundary with the short grasslands (Golzu and Nazu sites!).

The following summary may be given: Apart from small, isolated, strongly salt-affected areas in the west, salinity appeared to occur mainly as internal salinization in the flat eastern and in the weakly dissected north-eastern part of this soil landscape. Salinity and alkalinity were positively correlated as free carbonates and bicarbonates formed important components of the salt composition.
Below stands of Andropogon greenwayi, salinization was generally not found within a depth of 1 metre, except at the Nazu site.
In areas where Andropogon greenwayi patches formed mosaics with more open, rather short grassland types, soluble salt concentrations and alkalinity were always lower under the Andropogon greenwayi patches.

- CEC, exchangeable cations

Data on CEC and exchangeable cations were obtained from the NaNae 3 profile (Table 18), close near the Short grasslands, the NaNo-A and B profiles (Table 21) and the Na-Lag profile (Table 20). CEC values varied roughly between 40 and 50 me/100 gram of soil and were lower than those found for the soils of the Short grasslands, especially at lower depths (see Table 9). CEC data from NaNae 2 (Table 11) which was situated in the transitional zone between the "Short" and Andropogon greenwayi grasslands resembled those of NaNae 3.

Base saturation in the top 20-60 cm was less than 100%; the lowest values[F] found in the NaNo-A profile (Andropogon greenwayi spot): 78,7% in the 20-30 cm layer. Near the Short grasslands (NaNae 3 site) saturation in the surface soil was nearly 100%.

F: were

An important difference was found between the profiles NaNo-A and NaNo-B. CEC values for the NaNo-A profile (Andropogon greenwayi spot) were 10-20% higher, but base saturation in the upper 50 cm was considerably lower, possibly as a result of more intensive leaching porcesses that take place under the Andropogon greenwayi grass cover. In the NaNo-B profile (Digitaria macroblephara spot) exchangeable bases even exceeded the CEC values below 40 cm ("oversaturation").

A significant "oversaturation" was also found in the subsoils of the NaNae 2 and Na-Lag profiles. This phenomenon and its possible causes have already been discussed in paragraph 2.1.2d (BARSEK profile, Short grasslands).

The clay and silt percentages in the NaNo and Na-Lag profiles were higher than those in the BARSEK-profile in the Short grassland area (see Tables 15 and 5). It was pointed out before that if the mechanical analysis would have been preceded by pre-

Table 21 : cation exchange capacity and exchangeable cations in 2 profiles in the Andropogon greenwayi grasslands (NaNo - A, NaNo - B)

Na No Agre

CEC, ESP etc. (corrected) in meq/100 g

	CEC	Na^+	K^+	Ca^{2+}	Mg^{2+}	Total Bases	"H^+"
0-10	50.54	0.39	8.46	24.29	6.95	40.09	10.45
20-30	47.83	0.96	8.40	22.25	6.02	37.63	10.20
40-50	47.28	4.61	10.36	20.13	5.55	40.65	6.63
70-80	52.45	19.99	21.33	10.02	1.95	53.29	- (?)

Percentages:

	CEC	% Na	% K	% Ca	% Mg	Base Sat.	% "H"
0-10	50.54	0.77	16.74	48.06	13.75	79.32	20.68
20-30	47.83	2.01	17.56	46.52	12.59	78.68	21.32
40-50	47.28	9.75	21.91	42.58	11.74	85.98	14.02
70-80	53.29 (T.B.)	37.51	40.03	18.80	3.66	100.00	-

Na No Dima

CEC, ESP etc. (corrected) in meq/100 g

	CEC	Na^+	K^+	Ca^{2+}	Mg^{2+}	Total Bases	"H^+"
0-10	39.81	0.55	8.15	21.94	6.38	37.02	2.79
20-30	39.13	1.45	8.53	22.77	6.52	39.27	-
40-50	42.39	10.15	11.69	17.25	5.48	44.57	-
70-80	47.28	25.58	20.98	2.54	0.86	49.96	-

Percentages:

	CEC	% Na	% K	% Ca	% Mg	Base Sat.	% "H"
0-10	39.81	1.38	20.47	55.11	16.03	92.99	7.01
20-30	39.27(TB)	3.69	21.72	57.98	16.60	99.99	-
40-50	44.57(TB)	22.77	26.23	38.70	12.30	100.00	-
70-80	49.96(TB)	51.20	41.99	5.08	1.72	99.99	-

treatment of the samples with Na-EDTA - which had been applied to the BARSEK samples! - instead of hydrochloric acid (Oosterbeek method), the difference would have been even more prominent, especially in the calcareous C-horizons.

In view of the high clay+silt contents, the CEC values in the NaNo and Na-Lag profiles seem rather low. The following factors may be responsible for this:

1. Lower content of amorphous material with high exchange capacity, or transformation of amorphous materials into materials with lower exchange capacities, e.g. poorly crystallized clay minerals. In fact, the latter process may have taken place as a result of weathering processes which are more intensive than in the Short grasslands because of the higher mean annual rainfall and the increased biological activities (see 2.2.2: Biological activities) in the soil; preseumably in combination with:
2. Lower exchange capacities of the amorphous material due to lower pH values of the soil material (pH over 10,3 in the BARSEK profile!). N.B.: The CEC determinations were carried out under unbuffered conditions (see also Part I, Ch. 2: Methods).
3. Lacking of zeolites (present in the BARSEK profile!)

CEC determinations according to a modified method after Bascomb gave values that were of the same magnitude as those obtained by the standard methods (see Part I, Ch. 2: Methods).

Some remarks on the composition of the exchangeable cations:

The major difference between NaNo-A (Andropogon greenwayi spot) and NaNo-B (Digitaria macroblephara spot) was the strong increase of the amounts of exchangeable sodium below 40 cm in the NaNo-B profile, due to high contents of sodium salts. These amounts, however, were still much lower than in the BARSEK profile (Short grasslands) at corresponding depths (Table 21). Data from the NaNae 2 profile (Table 11, profile situated just within the Short grasslands, close to NaNae 3) are intermediate between the NaNo-B and BARSEK profile. The amounts of exchangeable calcium + magnesium in the NaNo-A and B profiles were about equal, in the top 30 cm, both relatively and absolutely. For the[F] soil layers, the highest amounts Ca+Mg were found in the less alkaline NaNo-A profile.

F: deeper

The relative amounts of Ca+Mg in the top soils of the NaNo, the Na-Lag and the NaNae profiles were of the same magnitude as those in the top soil of the BARSEK profile in the Short grasslands.
The relative amounts of exchangeable magnesium in the top soils (0-30 cm) of the NaNo and NaNae profiles were considerably higher than in the BARSEK profile; the advanced decalcification of the topsoils in the <u>Andropogon greenwayi</u> grasslands area may account for this fact.
In the Na-Lag profile, the relative amounts of exchangeable K were 1,5 to 2 times lower than in the other profiles; this explains the low amounts of soluble K throughout this profile.
The relative amounts of potassium in the other profiles did correspond fairly well with those in the soils of the Short grasslands (NaNae 2, BARSEK).

- <u>Lime</u>

Within the <u>Andropogon greenwayi</u> grasslands (I.2) a marked decalcification of the top soil was found. The thickness of the "non-calcareous" top layer - i.e. with lime contents in the fine earth fraction (fraction smaller than 1.7 mm) of less than 1% by weight - increased from 30 cm near the boundary with the Short grassland area to over 1.0 metre in the westernmost part of the <u>Andropogon greenwayi</u> grasslands. This gradient was based on data from profiles that were situated on flat ridge tops and extensive level areas ("flat plain"). Apart from this regional gradient there were local gradients as a result of the gently undulating topography: increasing thickness of the non-calcareous top soil down the slope due to a more intensive leaching.

Calcic horizons (over 15% lime in the fine fraction!) within a depth of 1.20 m are found in the area east and north-east of and around Naabi Hill. In soils of the ridges and the flat plain the upper boundaries of the calcic horizon were found at depths between 80 and 110 cm; contrary to the situations in the Short grasslands, these boundaries were rather abrupt. To the west and south-west of Naabi Hill no calcic horizons were found within 1.20 metre. Below 1 metre, however, hard or slightly indurated fine to coarse concretions were very common, locally abundant, while the percentage of lime in the fine earth fraction reached a maximum of about 8% at depths within 1.50 m (Na-Lag!).

In view of the relationships that exist between climate, namely the mean annual rainfall, and decalcification of a soil, the gradient of decalcification across the _Andropogon greenwayi_ grasslands seems somewhat steep with regard to the weak rainfall gradient within this area (see Part I, Climate, Fig. 6). It should be kept in mind that the number of data on the lime contents of the soils was limited and that the rainfall patterns have been based on short term data. It could be possible, for example, that a rapid increase of the thickness of the non-calcareous top soil occurs in the westernmost parts only, due to the presence of a steep local rainfall gradient that might exist on the windward side of the neighbouring Uplands. The weak gradient of decalcification in the flat central part of the area (around Naabi Hill) may support this idea.

2.2.2. Biological activity in the soil

a. Root development

The main mass of roots was found in the top 40-60 cm; below this depth the number decreased more or less gradually; at depths of 1.50 metres roots were still found, also in salt affected and very strongly alkaline parts of the C-horizon. In profiles with a well developed soil structure (e.g. A-horizon of vertisols in valley bottoms), most roots occurred on the faces of the structural elements and along cracks. Most of the roots were grass roots and could be arranged under the class "fine roots". Medium sized roots belonged mostly to herbs such as Indigofera basiflora, Justicia elliotii ,which occurred abundantly on flanks and in valley bottoms, Solanum incanum and Heliotropium steudneri, which were especially common on the flat plain south of Naabi Hill and on ridge tops.

b. Activities by insects

- Termites

Termite activity showed up in several ways:

- presence of termite mounds or termitaria built from subsoil material; they occurred in the area west of Naabi Hill. There were 2 types: low, rather flat mounds, up to 30 cm high and several metres diameter, bare when fresh, partially covered by grasses when old, which occurred on ridges and upper flanks (o.a. NaNo, Hiva-K and Old.Olobaie sites); large mounds up to 2 metres high, mostly covered by a luxuriant vegetation of tall grasses and herbs, which only occurred along the drainage lines of some tributaries of the Mbalageti River that originate near Old. Olobaie and drain towards the north-east
- presence of subterranean globular nests or fungus combs within

a depth of 1 metre (NaNo-S, Na-Lag), occupied by small termit up to 5 mm long, which resembled the specimens described from the Short grasslands (I.1).

In view of the distribution of termitaria it might be concluded that in the area east of Naabi Hill the termites are mainly subterranean while in the area west of Naabi Hill termites carry out their activities also above the ground.

Termite activity has important effects on the physical-chemical properties of the soils: at the NaNo site, for example, patterns of internal salinization of the soils, that changed over short distances and that were reflected by the presence of different grassland types, were found to be related with the presence and age of termite mounds. A detailed description of this phenomenon can be found in chapter 3 : Special features.

- ants

Small, dark brown ants up to 10 mm (species unidentified) were found in nests in the NaNo-A profile (*Andropogon greenwayi* spot).

- Dung beetles

Recent dung beetle balls up to 10 cm diameter have been recorded both in the soil profile and lying in small groups in the field (probably dug out by jackals). Contrary to the situation in the Short grasslands, the turning-over effects on the soil by dung beetles are estimated to be less important in the *Andropogon greenwayi* grasslands, especially west of Naabi Hill. Details on dung beetle activity have been given before (2.1.5).

- Larvae

Larvae - presumably *Melolontha* or *Polyphylla* sp. - were commonly found, especially in the densly rooted top 20 cm; many of the larger biopores have been formed by the activities of these larvae.

- Other evidence of activities by invertebrates

In the NaNo-A profile - under Andropogon greenwayi grassland - many fine earthworm-like excrements were found in the top 25 cm. No earthworm could be found, but this might be related with the season: the top 50 cm of the profile was dry at the time of description. The presence of earthworms in this area was shown before during infiltration experiments that were made on the broad ridge (just north of NaNo site) that formed the transition between soils of the Andropogon greenwayi grasslands (I.2) and those of the Long grasslands (I.3): during the infiltrations, that were carried out in a moist soil (there had been much rain before), several small earthworms (about 5 cm long) came to the soil surface.

Another interesting feature was the occurrence of numerous so-called "clay-balls": fine or medium sized spherical bodies, built up by concentric laminations, that tended to peel off under pressure; they had a clayey texture, and a consistency varying between hard and very hard when dry. Some had a small hole of about 1 mm. The nature of these elements is still unknown but they seem very likely to be related with insect activity, possibly dung beetles.

c. Mammals

Some parts of the Andropogon greenwayi grasslands were marked by the occurrence of numerous holes, locally in such abundance that car-driving became difficult. They occurred in the better drained parts, viz. the ridges, the flat parts around Naabi Hill extending as far as the Short grasslands and the Olduvai Gorge and the flat area that forms part of the main water shed between

the Lake Victoria and the Olduvai Gorge catchment areas.
Many of the holes were inhabited by the spotted hyena (Crocuta crocuta) in which case they are called "dens", and by warthog (Phacochoerus aethiopicus): holes or burrows. Usually the dens and burrows had several entrances and formed slightly elevated spots, which were often marked by vegetational differences,a.o. by the occurrence of herbs.
The dens and burrows may partially have been dug by the aardvark or antbear (Dorst & Dandelot, 1970). The presence of this animal in the Andropogon greenwayi grasslands has not been established which might be due to the noctural habits of this insect eater (termites!).
As a result of the digging activities calcareous C-horizon material of higher salinity and alkalinity - indicated by colour and the presence of lime concretions - was brought to the surface. This process had a similar effect on salt content and alkalinity of the surrounding soils - and, indirectly, on the vegetation - as the activity of termites; the "burrow" or "den" effects, however, are considered to be less severe because there is no continuous supply of salts for longer periods.

2.3. Soils of the Long grasslands (soil landscape I.3 or C-region)

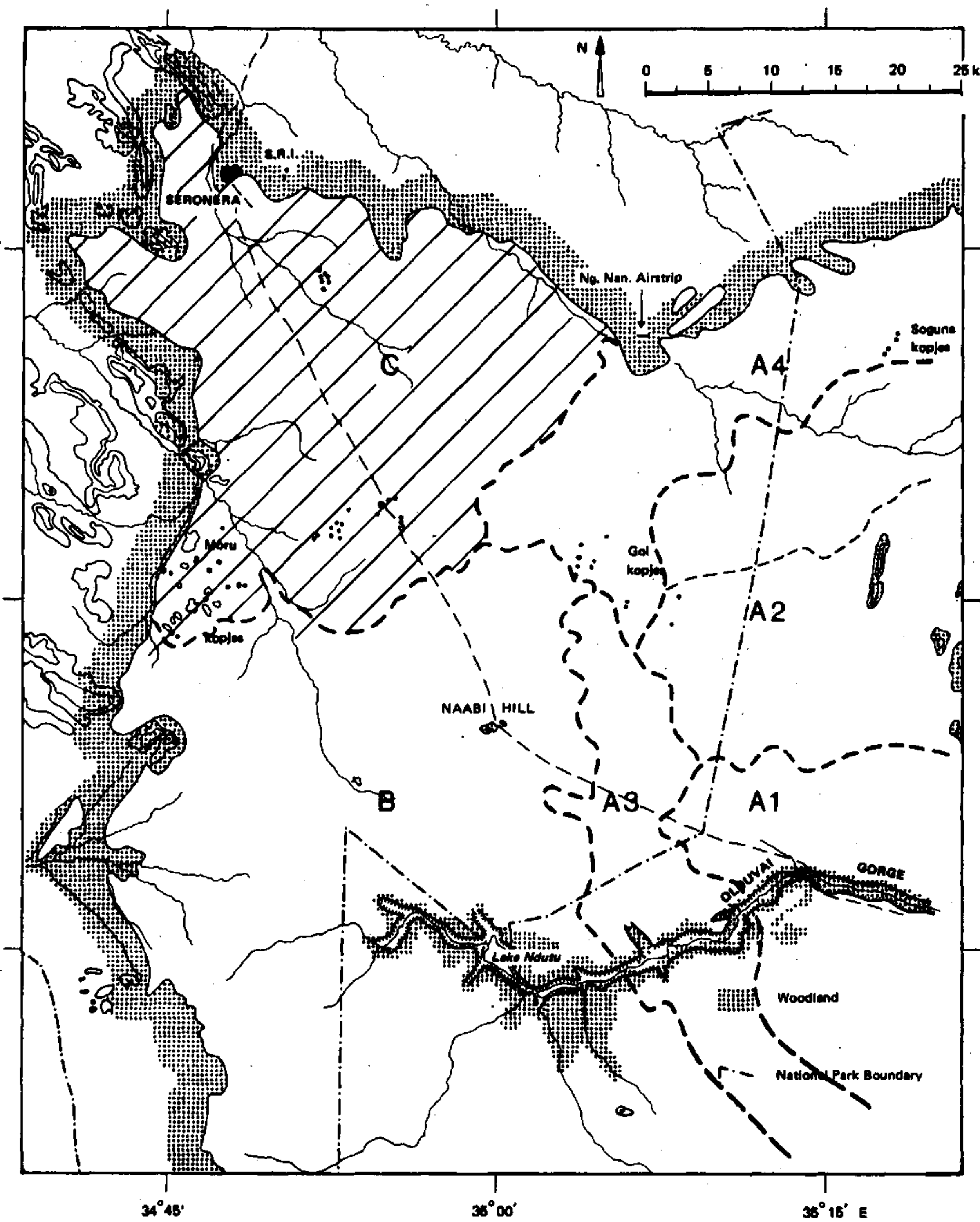
Loamy and clayey soils, containing certain amounts of residual materials (derived from weathering granitic, gneissic or quartzitic Pre-Cambrian rock), with a weak to strong horizon differentiation, with a non-calcareous top layer and locally saline or alkaline.

2.3.1. Soil characteristics

2.3.1.1. General description of the landscape, topography

The region indicated as soil landscape I.3 is marked by an

Fig 28: Boundaries soil landscape I.3



undulating topography, in which respect it differs strongly from the Andropogon greenwayi grassland area to the south of it, whereas it forms a continuation of the landscape in the north-western part of the Short grasslands that is found east of it. The boundaries of this soil landscape are shown in Fig. 28 . The elevation decreases from appr. 1700 m in the south-east to appr. 1500 m in the north-west; from the south-east towards the north-west the area becomes gradually more strongly dissected. Another important characteristic of the landscape forms the "long" grassland vegetation, in which the grasses may reach heights of 1 metre and from which the landscape has derived the name of "Long grasslands". Trees are occasionally found along the drainage lines in the south, south-east and east; they become increasingly common towards the north-west and form tree-lines along the seasonal rivers (Seronera River, Wandamu River and others) near the boundary with the woodlands of the Dissected Plain (broad soil landscape II). More information about vegetational characteristics will be given in Part III: Vegetation and soils.

Gerresheim (1974) defined the Long grasslands as Land Sub-Region 14, in which he distinguished some 12 landsystem associations (14.1-14.12) on topographic and vegetational characteristics. Within the landscape the ridges, flanks and valley bottoms formed well defined physiographic units, which showed up clearly as well in the field (especially in the dry season) as on aerial photographs. Striking features in this area - belonging to the so-called Miscellaneous landtypes - were the following:

1. "Kopjes" (outcrops of the Pre-Cambrian basement rock)

   There are three major groups of kopjes, all granitic:

- Moru kopjes in the south, bound by the Uplands to the west and by the *Andropogon greenwayi* grasslands to the south. The Moru landscape has been described in detail by Gerresheim (1974). The Moru kopjes are marked by both the large number and the size of the outcrops.
- "Simba kopjes" in the south(-east): less numerous than in the Moru area, also smaller sized.
- Masai kopjes, a rather small but striking group of outcrops which are situated on the top of a ridge in the north, not far from the boundary between the grassland and the woodland.

2. Quartz hills

flattened outcrops of the Pre-Cambrian basement; they occur in various places; most prominent are the four hills along the Seronera River.

Some more outcrops, although less conspicious, are found in the western part near the Oldoinyo Rongai hills and near the Olburturoto kopjes in the north, close by the Loliok site (to be discussed later on).

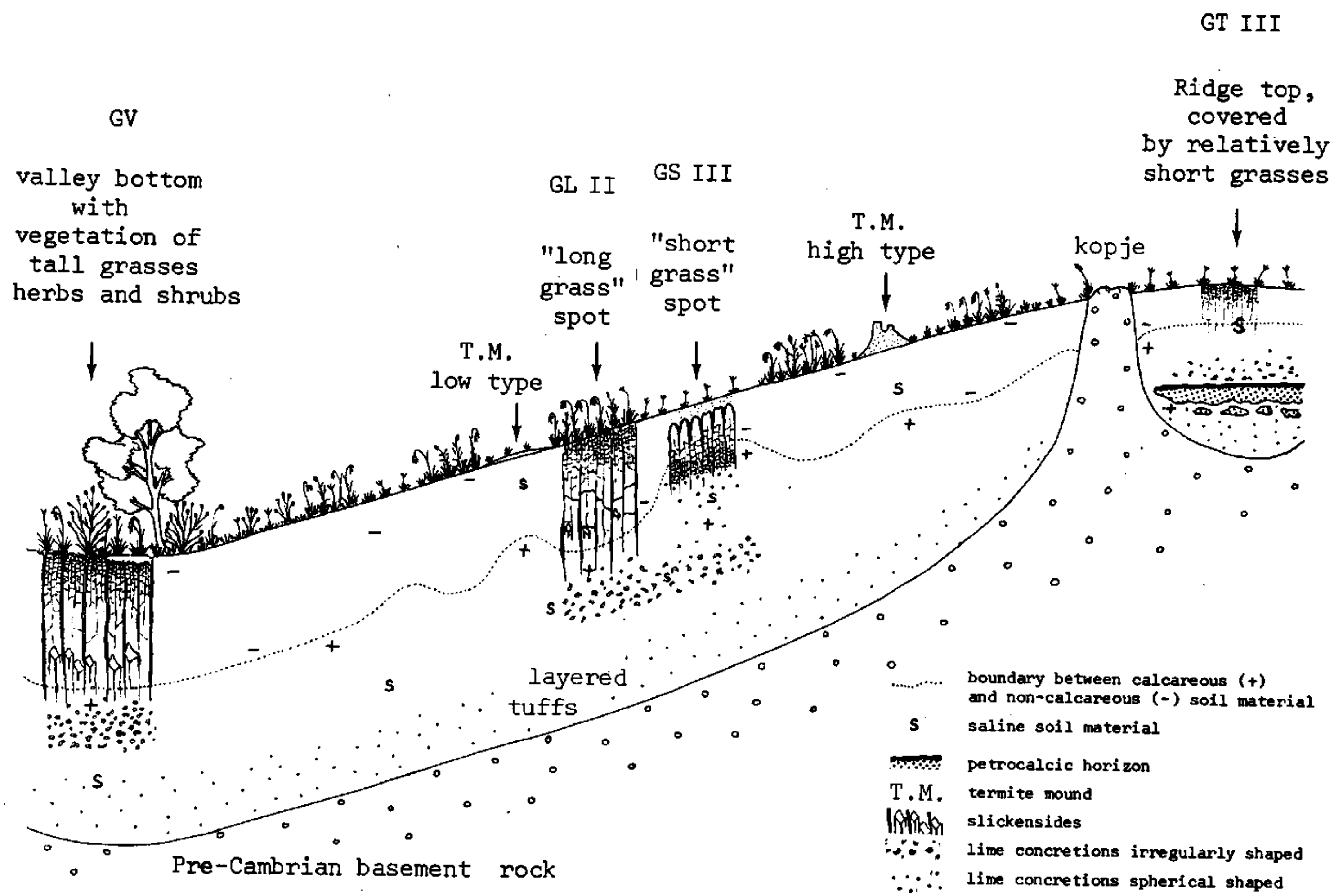
Several other ridges in the Long grassland area may be quartz veins that are overlain by only a shallow layer of ash: at those places rounded white quartz pebbles are commonly found, e.g. on the top of a ridge along the Gol track about 5 km east of the main road.

Besides quartz, also outcrops of quartzite and shales were found in recent and former gravel pits.

In the less dissected eastern and south-eastern parts, waterholes and scarps occurred; both features were more common in the adjacent Short grasslands.

The mean annual rainfall shows a clear gradient from the south-

Fig.29: Soil landscape I.3 (Long grasslands): cross section near Simba kopjes.



east (600 mm) towards the north-west (800 mm) which stands out most clearly along the north-western edge of the grassland plain (see Fig. 6 , Part I, Ch. 3: Climate).

2.3.1.2. Morphology

Most data have been collected from a catena along a 1-2% slope in the Girtasho area, near the Simba Kopjes; the Girtasho catena is shown in Fig. 29. In view of its location - app. 10 km from the boundaries with the Short and Andropogon greenwayi grasslands - the choice of the Girtasho sequence as a representative one for the entire Long grasslands may seem disputable. Data from a site which is located near the centre of the area (Sersi), however, showed little differences only. In the northern part near the woodlands, where soil properties were expected to be more different because of the increase of the mean annual rainfall, additional information was obtained from several soil pits at the Loliok site, near the Olburturoto kopjes.

- Soil structure

  Ridgetops: for profile desccription of the ridge top profile Girtasho III (GT III), see Appendix 29 . Structure was moderately to weakly developed in the dark coloured (very dark grayish brown) top layer (0-20 cm). Below this depth the soil had only a weakly developed structure while it became structureless at about 40 cm; below this depth the loamy soil material was calcareous, it had a high porosity (sponge or cavity structure) and its colour changed gradually from brown to yellowish brown. Below 70 cm, hard and variously shaped lime concretions did occur, increasing in number and size with the depth. At 1 metre a petrocalcic horizon was found; it differed from the petrocalcic horizons in the Short grasslands by its much lighter colour and stronger degree of cementation. In the top 40 cm,an important percentage of the soil aggregates was formed by hard fine and medium sphërical, laminated elements ("clayballs"); the "clayballs", however, are products of biological activity and differ strongly from natural soil aggregates by their compactness and higher clay content. The profile can be characterized as an A(-AC-)C profile. Halfway down the slope the profiles GS I, II, III and GL I and II were investigated. The vegetation at these sites was marked by the occurrence of a mosaic of short and tall grass spots; the short spot profiles have been indicated by the abbreviation GS (Girtasho Short grass), the tall grass spots by GL (Girtasho Long grass).

Between the "short and tall grass spot" profiles - detailed profile descriptions are given in Appendices 30 and 31 -

there were important differences in profile development. The "short grass" profiles had a thin (0-10 cm) loamy surface horizon with a weak to moderate subangular structure, abruptly overlying a heavy clayey layer (10-35 cm) with a strong medium and coarse columnar structure, quite massive above with some weak albic interfingering, falling apart into a sharply edged angular blocky structure below (compound structure); below 35 cm, the clay content, the class and the grade of soil structure decreased gradually to a depth of 110 cm, below which the soil was structureless. Common fine, hard, rounded lime concretions were found between 30 and 80 cm; below 110 cm soil material had a loamy texture and was rich in irregularly shaped lime concretions. The top 10 cm of the profile had a good porosity; very few pores were found between 10 and 65 cm in which zone all faces of the structural elements had very dark gray or black coatings, which probably consisted of dispersed clay and organic matter; below this depth porosity increased rapidly. The soil colours in the upper 1.0 metre varied from very dark gray to black when moist; below this depth, the colour turned (yellowish) brown (calcareous material!). Major soil horizon boundaries were abrupt and clear. Roots were largely concentrated in the upper 10 cm, while a limited number extended downwards between the columns.

The profiles at the tall grass spots had a clayey surface horizon of variable thickness (up to 20 cm) with a moderate subangular blocky structure overlying a thick clayey layer (20-80 cm) with a moderate or moderately strong coarse compound prismatic structure above, changing gradually into strong very coarse massive prisms below, separated by cracks up to 2.0 cm wide; coatings occurred abundantly between 35 and 80 cm. Below 80 cm the soil texture changed gradually to loamy and the structural grade decreased to almost structureless below 110 cm, at which depth the soil material was calcareous and rich in lime concretions. Soil colour in the top 80 cm varied between very dark gray and black; below this depth the colour turned gradually dark yellowish brown. In the upper 35 cm the so-called "clayballs" were commonly found. The horizon boundaries were clear or gradual. Roots were very common in the upper 35 cm and common till a depth of 80 cm or more.

F: flank

Summarizing: both[F] profiles were of the A-B-C type (B-texture). The major differences were found in the upper 80-100 cm and dealt with type of soil structure and distinctness of the horizon

boundaries. The strongly developed columnar B-horizon (natric horizon), the abrupt transition between A and B horizon in the "short grass" (GS) profiles, combined with the hampered root development, are a clear indication for physical-chemical properties that are less favourable for plant growth. The "short grass" profile is often called solodized solonetz; chemical data will be discussed later on. In the "tall grass" profile, the thicker A-horizon changed more gradually into the B-horizon, allowing more roots to penetrate to greater depth; the B-horizon was an argillic instead of a natric horizon. The A-horizon and upper part of the B-horizon of the "tall grass" profile showed a higher degree of biological activity (invertebratae) than the top soil of the "short grass" profile. From the morphological point of view, the "tall grass" profile could be expected to be more favourable for plant growth than the "short grass" soil. This will be illustrated later on in the discussion of physical and chemical aspects.
The differences between these two types of profiles just described, occur over short distances and are probably related with the effects of termite activity in a way comparable with situations described from the NaNo sites in the Andropogon greenwayi grassland (see Ch. 3 : Special features). This aspect will be dealt with later on, on the basis of chemical data.

The last profile of the catena (GV) was situated on the valley bottom (GV: Girtasho Valley). The soil had a very thick, black, heavy clayey, non-calcareous A-horizon, abruptly overlying dark yellowish brown calcareous C-material, rich in lime concretions, at a depth of about 1.30 metres (A-C profile). During the dry season the surface had cracks up to 3, locally even 5 cm wide, and was covered with a layer of very fine and fine granules ("mulch"). The cracks, narrowing with increase of depth, reached a depth of about 1.0 metre; between the cracks very coarse compound prismatic structures were found which could be subdivided into moderately strong and strong, fine and medium (sub)angular blocky elements. Between 70 and 110 cm, coarse slickensides were recorded with crushed remains of old roots across the faces. Roots occurred throughout the A-horizon: highest density was found in the top 20 cm.

The valley bottom profile had all characteristics necessary to be classified as a vertisol. Comparing the profiles of the various relief positions, the loamy ridgetop profile had little in common with the clayey flank and valley bottom soils.

To judge from soil colours, the weak grade of soil structure and the presence of a petrocalcic horizon, the ridge top profile resembled the soils of the Short grasslands (Soil landscape I.1). It should be remarked that the distribution of the G.T.III (ridge top) soil type is restricted to small areas on the very top of the ridges with a width or diameter of several hundred metres only; on the soil map these areas have been indicated by dotted boundaries within the ridge units. The ridge soils outside the loamy central parts are probably finer textured and will have a stronger horizon differentiation.

Towards the north-western part of the Long grasslands, the loamy ridge top soils change gradually into darker coloured, finer textured soils which had a stronger developed soil structure; there was also a marked increase in the amounts of residual material in the profile, especially in the surface-horizon and on the surface. The areas, occupied by the loamy soils as described from the Girtasho ridge top, become smaller into the same direction. The above south-east/north-west trends are all closely related with the increase of the mean annual rainfall - and consequently with the increase of natural erosion - across the Long grasslands, especially near the northern and western edge of the plain where the rainfall gradient is most steep.

Profile 8, a ridge top profile, located at the Loliok 1 site, not far from the boundary between the Long grasslands and the woodlands, illustrates the situation described above (profile description given in Appendix 32[1]). This profile had a structural B-horizon which might be - to judge from the presence of common dark coatings - an argillic horizon as well; the decalcification had progressed to a depth of at least 80 cm (versus 30-40 cm at the Girtasho ridge), which had resulted into the presence of a great mass of extremely hard, irregularly shaped, lime concretions below 85 cm. Residual materials - for the greater part consisting of coarse reddish quartz grains (or very fine gravel), derived from Pre-Cambrian basement rock - occurred abundantly near and on the surface. Much of the very fine quartz gravel - washed out by precipitation - collects in the shallow depressions between grass clumps; this phenomenon - often called "sand wash" - forms a striking feature in the northern part of the Long grasslands, especially around kopjes, on tracks and in areas affected by sheet erosion.

Profile 9 (Loliok 2 site; profile description given in Appendix 33[1]) was located down a gentle slope less than 1 km south of profile 8, near the boundary between ridge and flank. The profile was a typical A-B-C profile; the textural B-horizon had a compound pris-

[1] available at the Dept. of Tropical Soil Science, Agricultural University, Wageningen, Holland.

matic, locally tending to columnar, structure with abundant dark coatings on the faces of the structural elements. No petrocalcic horizon was found within a depth of 1.60 metres, but hard lime concretions formed the greater part of the soil material below 1.50 metres.

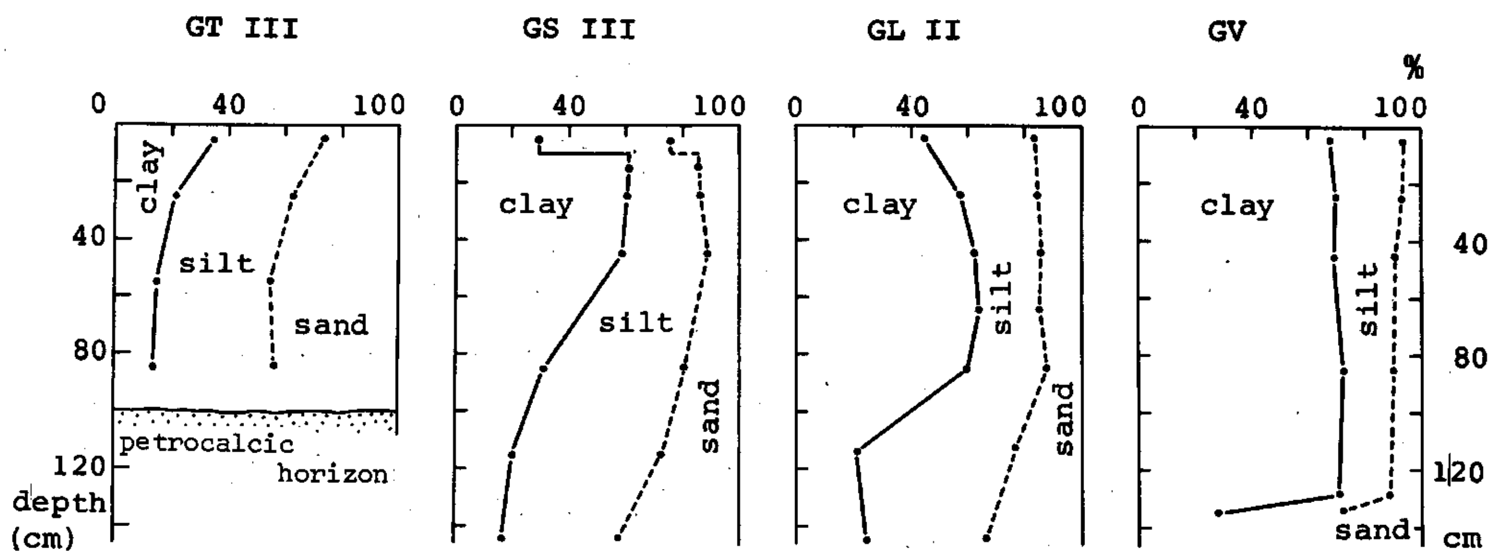
A somewhat different catenary system is found in the Moru area, well known for its great number of large Pre-Cambrian outcrops (kopjes or inselbergs). The granitic rocks and their pediments - rich in very fine quartz gravel - disturb the general relief pattern (ridge , flank , valley bottom soils) in many places since they occur in all possible relief positions. Most soils in the area have been influenced by the weathering products of the granitic substratum.

A soil unit, characteristic for the Moru landscape, is formed by the so-called drainage depressions: very shallow, broad depressions without a well defined riverbed or drainage line, that extend from the base of many of the kopjes towards the valley bottoms of the major river coarses. The drainage depressions have black, very heavy clayey soils, marked by wide cracks in the dry season; during the wet season and even during the first months in the dry season, these soils suffer from impeded drainage, largely due to the supply of water from springs, that originate at the base of the kopjes. In view of the fact that the distribution of this soil type appeared largely limited to the Moru area, and that the soil properties were probably not very different from heavy clayey soils of valley bottoms in the same area, the drainage depressions have been included within the broad soil unit "clayey soils of valley bottoms and riverbeds", with a moderate horizon differentiation (I.3.3). Details on the Moru landscape are found in Gerresheim (1974).

Finally, three other features, that commonly occur within the long grassland area, should be mentioned:

- Depressions up to 1.0 metre deep, incised in the riverbeds or drainage lines: they are mostly bare - colonization by grasses (e.g. Cynodon dactylon) has been recorded locally - with wide cracks at the bottom, often covered by a mulch layer. Gerresheim (1974) gives dimensions of 10-60 metres long by 2-6 metres wide. During the wet season and also for some time afterwards, the depressions from isolated pools that are frequently visited by game animals (wallows). The origin of these depressions has not been investigated, but erosion processes and local variations in the physical chemical stability of the heavy clayey soil play probably an important role. Game animals may enlarge existing depressions or start new ones.
- Scabby spots or slick spots: truncated solodized solonetz; these spots are found on the flanks in places where the thin A-horizon of the solodized solonetz ("short grass" spots!) has been removed totally or partially by wind or water erosion, possibly in combination with digging activities of wild animals, leaving the columnar or strong prismatic structures exposed. The spots are bare or support a sparse grass vegetation.
- Scarps, waterholes: these features occur in the eastern parts (Transitional zone) near the boundary with the Short grasslands. Most are situated on the ridge tops and show great resemblance with corresponding features in the adjacent Short grasslands; some details have been discussed in the description of the Short grassland soils.

Fig.30: Soil landscape I.3 (long grasslands: Girtasho sequence): clay, silt and sand contents throughout 4 characteristic profiles; contents as percentages of the total mineral fractions (Oosterbeek method, see part I, Ch.2: Methods).



GT III: ridge top near Simba kopjes
GS III: flank, short grass spot
GL II: flank, tall grass spot
GV : valley bottom

2.3.1.3. Physical characteristics

- Soil texture

Fig. 30 shows distribution of clay, silt and sand fractions in four profiles of the Girtasho catena; the figures have been listed in Table 22 , and more extensively in Appendix 34 . The textural differences between the profiles, that were already mentioned partially under morphology, show up clearly: In the ridge top profile (GT III) the highest clay contents are found in the top layer (0-10 cm); between 10 and 40 cm there was a decrease of the clay content accompanied by an equal increase of the sand fraction; below 40 cm (C-horizon) the clay, silt and sand fractions were constant down to the petrocalcic horizon. In the solodized solonetz (GS III, "short grass" profile), the soil texture of the homogeneous top 10 cm was almost similar to that of the ridge top soil. At 9(-10) cm there was an abrupt increase of the clay content of over 2 times: top of the columnar B-horizon. Below 60 (-65) cm the clay content decreased gradually while the percentage of the sand fraction increased; in the C-horizon (140-150 cm) the distribution of the clay, silt and sand fractions resembled the situation in the C-horizon of the ridge top profile (GT III).
In the "tall grass" profile (GL II), the surface horizon had a finer texture than in the previous profiles; the clay percentage increased much more gradually from the A towards the B-horizon, while the sand percentages were nearly constant.
In comparison with the B-horizon in the "short grass" soil (GS III), the B-horizon in the long grass profile had a greater thickness; the soil textures, however, were quite similar. The decrease of the clay percentage from the B- towards the C-horizon (80-120 cm)

Table 22: Soil landscape I.3 (Long grasslands): Soil texture [1])

Girtasho ridge top (G.T.III) [2])

depth (cm)	% < 2 µm	% 2-50 µm	% > 50 µm
0-10	34.1	38.9	27.0
20-30	20.7	41.9	37.4
50-60	14.6	40.9	44.5
80-90	14.3	42.1	43.6

Girtasho flank, short grass spot (G.S.III) [2])

depth (cm)	% < 2 µm	% 2-50 µm	% > 50 µm
0- 9	28.9	48.1	23.0
9-20	61.1	24.7	14.2
20-30	60.7	26.2	13.1
40-50	59.1	30.4	10.5
80-90	31.1	49.8	19.1
110-120	20.4	52.9	26.7
140-150	16.9	40.9	42.2
20-30 [3])	60.0	28.6	11.4

Girtasho flank, tall grass spot (G.L.II) [2])

depth (cm)	% < 2 µm	% 2-50 µm	% > 50 µm
0-10	44.7	39.2	16.1
20-30	57.3	27.6	15.1
40-50	62.4	23.8	13.8
60-70	64.1	21.8	14.1
80-90	60.2	27.6	12.3
110-120	21.6	54.9	23.5
140-150	24.8	42.5	32.7

Girtasho valley bottom (G.V.) [2])

depth (cm)	% < 2 µm	% 2-50 µm	% > 50 µm
0-10	67.2	26.3	6.5
20-30	70.1	22.8	7.1
40-50	69.0	21.7	9.3
80-90	71.4	18.4	10.2
128-140	28.7	43.3	28.0
80-90 [3])	73.8	17.6	8.5

"Vertisol of lithomorphic origin" [4])

depth (cm)	% < 2 µm	% 2-50 µm	% > 50 µm
0-12	30.7	31.6	37.7
12-30	32.3	35.2	32.5
30-60	13.0	32.0	55.0

[4]) results given by Anderson & Talbot (1965); for methods used for mechanical analysis see Table 16.

"Brown calcareous soil" [4])

depth (cm)	% < 2 µm	% 2-50 µm	% > 50 µm
0-20	23.0	24.1	52.9
20-35	22.3	24.3	53.4
35-55	10.0	30.8	59.1

[1]) all fractions as percentages of the total mineral fractions.

[2]) mechanical analysis acc.to methods used at Oosterbeek (see Methods)

[3]) sample treated with Na-EDTA, buffered at pH 5.0-6.0 by Na-acetate. in order to dissolve lime and to disperse the particles.

was more abrupt; textural differences between the two C-horizons were small.

The valley bottom profile (GV) was a typical vertisol. The clay, silt and sand percentages were nearly constant throughout the thick A-horizon (0-128 cm); there was a weak increase of the sand content. Below the abrupt boundary between A and C horizon at 128 cm the soil material became rapidly coarser textured.

Two samples from the Girtasho sequence (GS III 20-30 cm and GV 80-90 cm layers) were treated with Na-EDTA and Na-acetate buffer solution to remove lime and disperse the particles without affecting amorphous materials: the results obtained in this way corresponded very well with the Oosterbeek-figures(in which case the amorphous material had been removed); this proved that the possibly present amount of amorphous material (see mineralogy) was equally distributed throughout the clay, silt and sand fractions.

The data given by Anderson and Talbot (see Table 22) are difficult to compare with the Girtasho figures and other data collected from the Long grasslands by the present author. Whereas the profile description by Anderson & Talbot of the "Vertisol of lithomorphic origin" - the profile was located on a flank in the Girtasho area and showed a great similarity with the profile description of the solodized solonetz found at "short grass" spots (GS III etc.) - indicated a well developed A-B-C profile, the textural data do not show such a differentiation. This discrepancy must be due to the methods followed in the mechanical analysis which had evidently resulted into an incomplete dispersion of the particles.

The "Brown calcareous soil" as defined by Anderson & Talbot (1965) - located near the centre of the Long grassland area (Sersi site) -

has much in common with the ridge top profile at the Loliok site (profile 8) in the northernmost part of the Long grassland: A(-B-)C profile; this "Brown calcareous soil" had fairly coarse textures throughout - even coarser than the Girtasho ridge soil (GT III) - which may be attributed again to the analysis procedures mentioned by both authors.

Contrary to the data collected by the author, the figures given by Anderson and Talbot (1965) on the Long grassland soils'textures did not fit very well into the overall pattern of "advancing maturity" of the soils that is found across the Serengeti Plain from the east towards the west and north-west, i.e. an increase of structural development, heavier textures, progressed leaching effects, etc. Anderson and Talbot ascribed this fact to the different origin of the soils in the north-west, which would have derived from a "calcareous conglomerate" with little, if any, ash addition. Pickering (1960) also mentions the occurrence of limestonelike rock from which gray brown soils of the grassland would have derived. Macfarlane (1967) thinks that the "light brown secondary limestone" in the north-western part of the plain to have been derived by the reworking of the calcareous tuffs of the Bed V of the Olduvai Gorge sequence. "The grey brown soils of the Serengeti Plain overlie and are weathering products of this secondary limestone".

Considering the profile development as described for the ridge top soil in the Girtasho area (GT III), and considering the similarity which exists in this respect between the latter profile and soils of the ridges in the adjacent Short grasslands (typical volcanic ash soils!), the secondary limestone or calcareous conglomerate hypothesis according to Macfarlane seems disputable. Mineralogical data, which will be discussed in the next paragraph, support this view.

- Mineralogy

A summary of some mineralogical characteristics of the 4 standard profiles of the Girtasho sequence (clay fractions only) is given. Diffractograms of the samples investigated - also of samples from soils of the other soil landscapes - are available at the Dept. of Tropical Soil Science, Agricultural University, Wageningen, Holland.

Girtasho ridge top (GT III): diffractograms of samples from the top-layer (A-horizon) and the calcareous subsoil (C-horizon, just above the petrocalcic horizon) were nearly identical. The peak at 4.5 Å (various crystalline clays) was more pronounced in the subsoil sample. In the samples of the top layer and the subsoil there was a broad low peak between 10 and 14 Å with its maximum at 10 Å: mixed layer as a result of weathering mica. The diffractograms of the subsoil sample also showed a low peak at 14 Å.

Amorphous material was the dominant component of the mineral fraction.

Girtasho short grass spot (GS III, solodized solonetz): the top (0-9 cm) sample showed a diffractogram nearly similar to that of the top soil of the ridge top profile; the peak at 4.5 Å, however, was less conspicuous, indicating a more advanced stage of weathering of clay minerals. The low 10-14 Å peak (mixed layer) was similar to the one found for the 0-10 cm sample of the ridge top profile. In the subsoil samples (B-horizon: 20-30 cm; C-horizon: 140-150 cm) the peak around 10 Å (-14 Å) showed up more clearly, indicating higher amounts of mica and its weathering products.

Amorphous materials, however, were dominant.

Girtasho tall grass spot (GL II): the top 10 cm gave a picture that differed from the ones of the GT III and GS III top soils; the peak around 10 Å was much more conspicuous: the diffractograms closely resembled that of the samples from the B and C-horizons of the former profile (GS III). In the GL II B-horizon sample (20-30 cm) the 10 Å peak was more distinct than in the A-horizon; between the A and C-horizon (140-150 cm) samples, differences were small.

Girtasho valley profile (GV): compared with the preceding surface samples, the diffractogram of the 0-10 cm sample is marked by a clear peak at 10 Å (mica); also the mixed layer is found. Between 80 and 90 cm - in which layer slickensides were found - the diffractogram was fairly similar to that of the 0-10 cm, but the range above 10 Å including the 10 Å peak, was at a somewhat higher level.

The sample from the C-horizon gave results that were very similar to those of the C-horizon material in the other profiles of the Girtasho catena.

The following conclusions can be drawn:

The diffractograms of the samples from the Girtasho sequence (Long grasslands) did not show any essential difference in mineralogical composition. Amorphous materials predominated in the clay fractions of all samples. In the clayey soil layers (B-horizon of GS III and GL II, A-horizon of GV), peaks between 10 and 14 Å were more pronounced than in the loamy soils or soil layers (GT, and C-horizons of the flank and valley bottom profiles). The clay accumulation in the B-horizons of the flank soils should be considered to be the result of illuviation processes only.

When comparing the Girtasho diffractograms with those obtained from samples from the other soil landscapes (I.1, Short grasslands and I.2, Andropogon greenwayi grasslands), the differences in mineralogical composition in the clay fractions are - in spite of the marked differences in soil texture, profile development and climatic conditions - surprisingly small.

One might conclude that all soils within broad soil landscape I (Sediment Plain) are very young or equally young and that local differences in climatic conditions (rainfall!) have not yet had an effect on local differences in the forming of clay minerals. What remains is the problem of the occurrence of swelling and shrinking soils (Long grasslands, Andropogon greenwayi grasslands:flank and valley bottom soils) and soils that do not swell or shrink at all (Short grasslands, ridge soils of Long and A.greenwayi grasslands), whereas besides the great similarity in mineralogy the textural differences are not extreme: e.g. a factor 1,5-2 higher for A and B-horizons in the Long and A.greenwayi grasslands in comparison with A-horizons of Short grassland soils. Lime may be a clue to this problem: all non-swelling soils or soil layers are calcareous, whereas the swelling soils are not. In calcareous soil material, the clay

F: set particles are[F] in a matrix of calcium-magnesium carbonate. It would be interesting to find out to what extent this configuration of the minerals will prevent swelling or shrink.

To obtain a better picture in the mineralogy of these soils elemental analysis on clay and total soil was carried out (see Part I, Ch. 2: Methods). The results are still an object of study and discussion. They have been given in Appendix 45.

Attention was also paid to the sandfractions (50-420 µm) of the samples (Appendix 46). The percentage of heavy minerals appeared to be the highest for the soils of the Short and Andropogon greenwayi grasslands while the percentages in the A-horizon samples were significantly higher than those of the C-horizons. The percentage for the Long grassland soils tended to be lower, especially for the A-horizon samples. The light fractions of the Long grassland samples were marked by relatively high amounts of reddish quartz grains (absent in the Short grassland samples!), showing the influence of residual materials from the Pre-Cambrian basement.

Very low percentages of heavy minerals were found for a profile near the Research Institute (SRI III : Dissected Plain, soil landscape II.2) forming an indication for the different nature of the parent material of the soils outside the Sediment Plain.

- Bulk density

On the whole, bulk densities of the Girtasho soils were higher than those of the soils of the other soil landscapes: whereas in the "Short grassland" soils the average bulk densities were mostly lower than 1.0 and in the *Andropogon greenwayi* grasslands the average values varies between 0.95 and 1.15, bulk densities of over 1.20 g/cm^3 were recorded in the Long grasslands (Table 23 , Appendix 35[1]). The increase of the bulk density from the south-eastern part of the study area (Short grasslands) towards the north-western part (Long grasslands-woodlands) can be ascribed to changes in soil structure and porosity (sponge structures changing into less porous, blocky and prismatic structures) that are the result of the advanced soil formation (see morphology). Variations in the bulk densities between different soil horizons within one profile and between the samples from various profiles of the Girtasho sequence were determined by a number of - partially interrelated - factors, such as structural development, porosity, root density, mineralogy, organic matter contents and clay illuviation (see soil texture).

In the ridge top profile (GT III) the bulk density was found to increase with depth; this was accompanied by a decrease of the organic matter and clay contents and a weaker degree of aggregation, probably in combination with a decrease in the pore space.

The loamy top layer of the solodized solonetz (GS III) had a higher bulk density (1.20 g/cm^3) than the surface horizon of the ridge top soil (GT III: 1.05 g/cm^3) although differences in micromorphological and mineralogical respects, and also in vegetation cover and composition were small. The interaggregate porosity in the GS III top layer was likely to be lower, for which the lower infiltration rate formed an indication (see

Table 23

Girtasho sequence (Long grasslands - I.3):

Average bulk densities and soil moisture contents at various moisture tensions in a desiccating soil; coefficient of linear extensibility (COLE)

Profile, horizon depths (cm)	ring sample depths (cm)	n[1])	bulk density (g/cm^3)	moisture contents (vol%) at pF 1	pF 2	pF 4.2	pF 5.6	SP	COLE[2]) (cm/cm)
G.T.III (ridge top)									
0-20	7.5-12.5	3	1.05	55.5	41.0	20.7	11.2	55.0	0.0
20-42(40)	26 -31	4	1.13	54.9	40.9	18.7	10.9	41.5	0.0
(40)42-73(70)	52.5-57.5	3	1.21	53.3	41.7	16.0	11.1	33.9	0.0
G.S.III (flank, short grass spot)									
0-9(10)	2.5-7.5	4	1.20	51.9	37.7	16.1	10.1	44.2	0.002
9(10)-32	21 -26	5	1.18	52.3	48.4	34.3	22.0	80.1	0.086
32-65	45 -50	5	1.16	53.3	47.1	32.7	21.8	79.7	0.029
65-110	90 -95	5	1.14	52.2	44.0	31.1	20.6	64.1*	0.014
G.L.II (flank, tall grass spot)									
0-20	2.5-7.5	4	1.15	51.4	39.6	22.4	13.6	61.8	0.013
20-33	21 -26	3	1.14	51.1	41.5	25.6	16.5	69.7	0.037
33-80	52.5-57.5	6	1.23	51.3	47.4	30.5	19.9	70.8*	0.070
80-110	94 -99	5	1.20	52.6	48.7	29.4	19.3	64.9*	0.032
G.V.(valley bottom)									
0-10	2.5-7.5	1	0.68					85.1	
20-30	22.5-27.5	1	1.04					80.8	
40-50	42.5-47.5	1	1.14					80.7	
50-60	52.5-57.5	1	1.17					81.9*	
80-90	82.5-87.5	1	1.24					86.6	
90-100	92.5-97.5	1	1.24					84.4*	

1) Number of samples

2) For brief explanation see Table 16

* Calculated by interpolation of SP-values of overlying and underlying 10 cm layers.

infiltration).

Comparison between surface soil (1.20 g/cm^3) and subsoil values (1.18 in the 9-32 cm layer, 1.16 in the 32-65 cm layer) of the GS III profile is more difficult since the bulk density measurements on the subsoil samples were disturbed by the swelling and shrinking properties of the clay fraction (see COLE data in Table 23 and Part I, Ch. 2 : Methods). The disturbing effects appeared most strongly at high percentages of exchangeable sodium (GS III 9-32 cm: columnar B-horizon). The method followed in the bulk density determination (starting with a saturated, swollen sample of 100 cm^3, which volume became reduced during drying at 105°C , see Appendix 35[1] had probably led to too low bulk density values. Under natural conditions the swelling of soil aggregates may be restricted by the internal stress in the soil which depends on weight of the overlying soil layer and swelling pressure from the surrounding soil material.

The bulk density measurements on the GL II samples (tall grass spot profile) were similarly disturbed, although the additional effect of high amounts of exchangeable sodium was lacking (see chemical characteristics).

An especially low bulk density was found in the surface soil of the valley bottom profile: 0.68 g/cm^3; numerous interaggregate pores and cracks, a very high root density, combined with swelling and shrinking effects, were the causes for this low value. At increasing depth, the bulk density values went gradually up to values comparable with those found in the other profiles.

- <u>Water retention and available moisture</u>

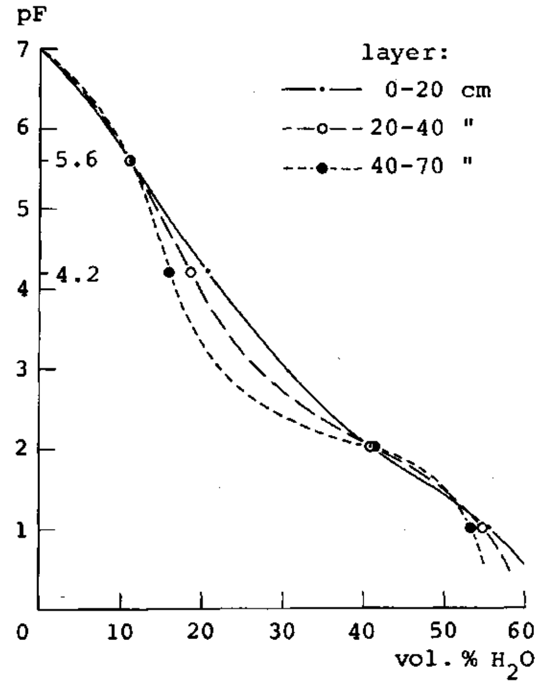
Data on water retention and available moisture have been obtained from the ridge top soil (GT III) and from the flank profiles GS III (short grass spot) and GL II (tall grass spot).

Water retention characteristics (pF-curves) have been outlined in Figure 31; the accumulated amounts of soil moisture at various tensions as well as the accumulated amounts of available water in Figure 32; availability trajects and average values per 10 cm layer of soil are given in Table 24 (deduced from the data in Table 23).

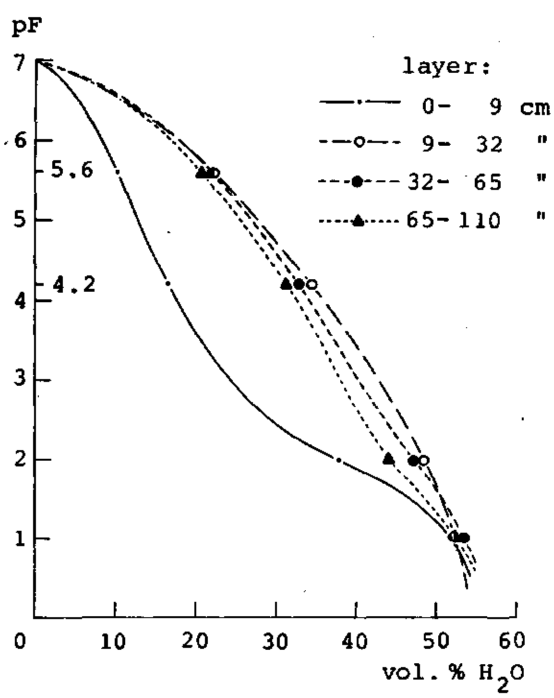
In the ridge top soil the pF-curves, that were found for the three horizons distinguished, were fairly similar. There was a lowering of the moisture content at the Permanent Wilting Point (PWP=pF 4,2) with increasing depth; this had resulted into a somewhat broader availability traject (mm at pF 2,0 - mm at pF 4,2) below a depth of 40 cm. The availability traject based on the amount (mm) at 1/3 bar (pF 2,5) minus that at pF 4,2, however, appeared to be less favourable than in the upper 40 cm (Table 24) because of the relatively low moisture content at pF 2,5 (value derived from the curve!).

The GS III (flank, short grass spot) characteristics showed an important difference in moisture retention between the thin loamy surface layer (0-9 cm) and the clayey alkaline part of the soil below it. The 0-9 cm curve showed great resemblance with the ridge-top (GT III) curves, especially with the one found for the 40-70 cm horizon. The three other curves, and namely the one for the 9-20 cm layer (natric horizon!) are typical for a heavy clayey soil. The potential amount of available moisture in the loamy top layer (mm at pF 2,0 - mm at pF 4,2) appeared to be at least 1,5 times higher than in the other parts of the profile (calculated per 10 cm layer). In case the moisture contents at

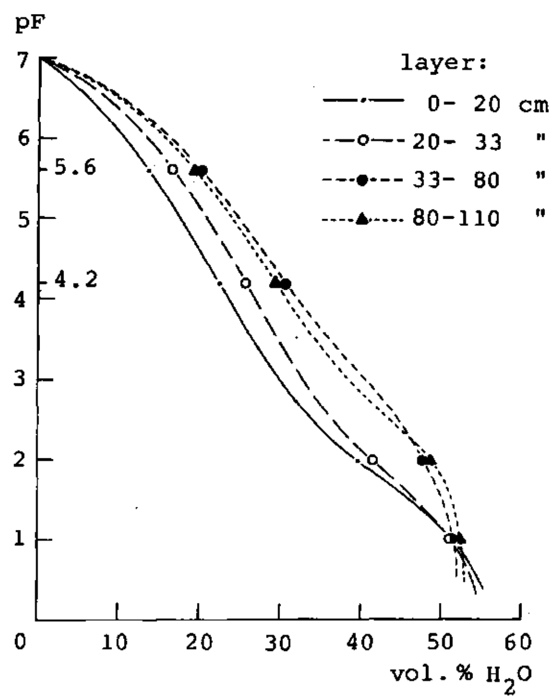
Fig.31: Soil landscape I.3 (Long grasslands): Moisture retention curves for various soil layers in 3 characteristic profiles (Girtasho area, near Simba kopjes).



a: GT III (ridge top).

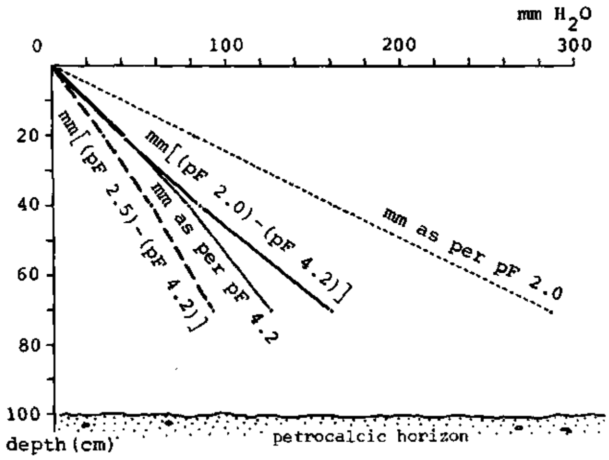


b: GS III (flank, short grass spot).

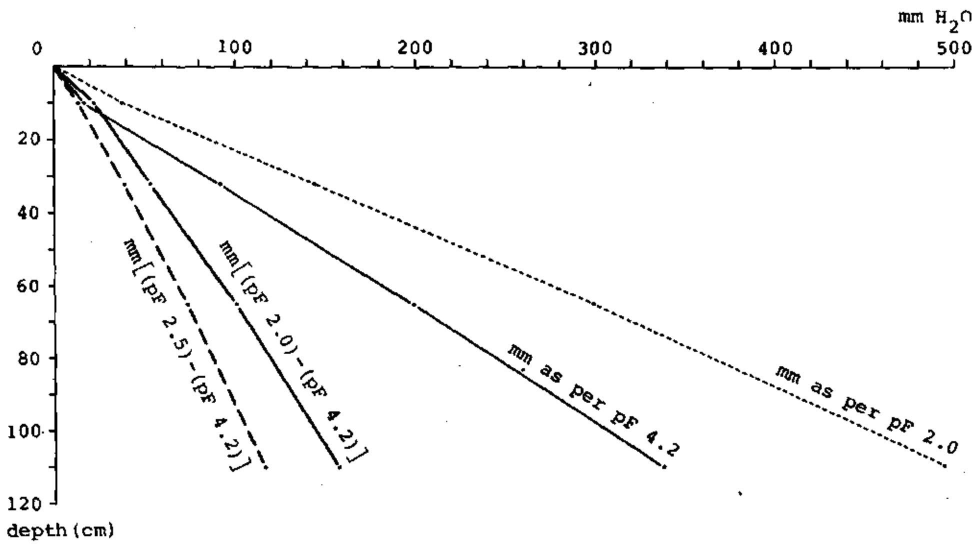


c: GL II (flank, long grass spot).

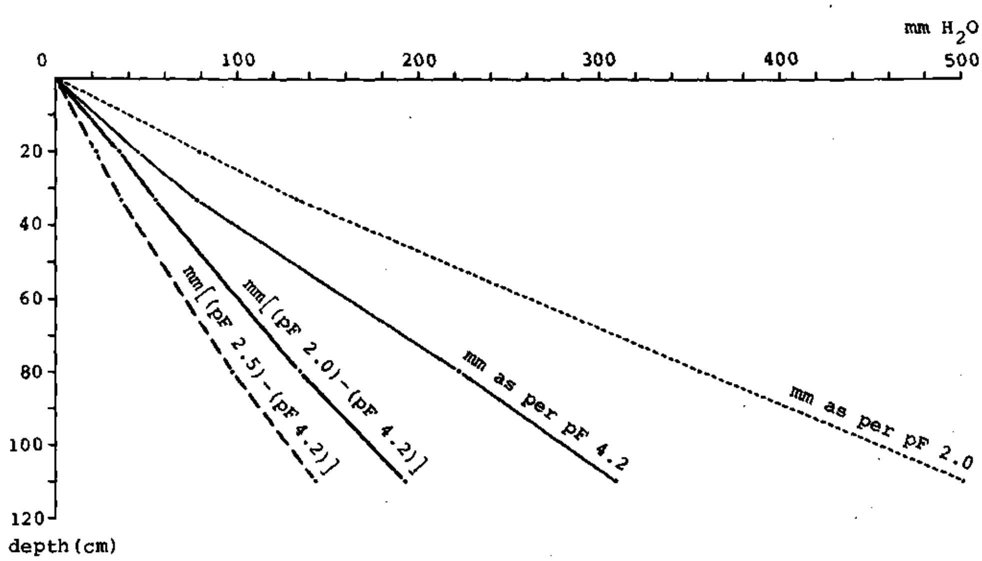
Fig.32: Soil landscape I.3 (Long grasslands): Amounts of soil moisture at pF 2.0 and pF 4.2 (mm) and amounts of available moisture (mm) accumulated with depth for 3 characteristic soil profiles (Girtasho area, near Simba kopjes).



a: GT III (ridge top).



b: GS III (flank, short grass spot).



c: GL II (flank, long grass spot).

Table 24

Girtasho sequence (Long grasslands) : potential water availability

profile, depths (cm)	available moisture [1] (mm) as per traject pF 2.0 - pF 4.2	average amounts (mm) per 10 cm layer	as per traject pF 2.5 - pF 4.2 [2]	average amounts (mm) per 10 cm layer
G.T.III				
0-20	40.6	20.3	29.6	14.8
20-40	44.4	22.2	27.6	13.8
40-70	77.1	25.7	36.0	12.0
0-70	162.1	23.2	93.2	13.3
G.S.III				
0-10	21.6	21.6	13.1	13.1
10-32	31.0	14.1	25.1	11.4
32-65	47.5	14.4	35.3	10.7
65-110	58.1	12.9	42.7	9.5
0-110	158.2	14.4	116.2	10.6
G.L.II				
0-20	34.4	17.2	22.2	11.1
20-33	20.7	15.9	14.2	10.9
33-80	79.4	16.9	61.1	13.0
80-110	57.9	19.3	45.6	15.2
0-110	192.4	17.5	143.1	13.0

1) For the calculations the moisture contents at pF 2.0 and pF 2.5 (1/3 bar) were assumed to be constant throughout the soil horizons distinguished.

2) Moisture contents ap pF 2.5 estimated from the pF-curves.

pF 2,5 (1/3 bar) are taken into account, the difference was smaller.

In the GL II profile (flank, tall grass spot), the differences in moisture retention between surface soil and subsoil were less striking.

Comparing the wateravailability of the 3 profiles investigated on the basis of the data given in Table 24 one may conclude that, potentially, the loamy ridge top profile (GT III) can hold the highest amount of available moisture (mm) in the upper 70 cm; the clayey "tall grass" profile (GL II) was less favourable, while the "short grass" profile GS III had the least favourable properties in this respect. The differences were most pronounced on the basis of the availability traject between pF 2,0 and pF 4,2 (respectively 162, 118 and 107 mm); on the basis of the pF 2,5 - pF 4,2 traject, the differences were considerably less (resp. 93, 85 and 78 mm).

For several reasons the above amounts are difficult to compare. One of them is the factor salinity, which lowers the water availability for sensitive grass species as a result of the increased osmotic value of the soil moisture. In the GT III profile the soil was strongly saline below a depth of 40 cm; the GS III profile was slightly saline below 40 cm. Comparing the salt-free top soils (0-40 cm) of the 3 profiles, the potential amounts of available moisture are (for respectively GT III, GL II and GS III): 85, 67 and 64 mm if the pF 2,0 - pF 4,2 trajects are taken into account and 57, 46 and 47 mm in case of the pF 2,5 - pF 4,2 trajects. The ridge top profile (GT III) is still the most favourable, the difference between the two flank profiles (GL II and GS III) was negligible.

Another point is that the above facts and conclusions are entirely based on data that had been obtained from experiments on desiccating soil. This situation can be compared with a soil that starts to dry out by evapotranspiration after a prolonged period of rainfall, e.g. at the end of the short or long rains (November, resp. May). Before the onset of the rains the soil has a moisture content in the rooted zone near pF 4,2. Upon wetting the pF-characteristics of the soils will show - if compared - the so-called hysteresis effect (Schofield, 1935; loc.cit. in E.W. Russel, 1961): at a given matric suction the soil will hold less water when it is wetted than when it is drying.

For the ridge top soil - non swelling soil material with a homogeneous porosity, especially at lower depth - the hysteresis effect may be expected to be small while both curves will maintain their shapes and positions after rewetting and draying out again ("stable" curves). For the clayey flank profiles the situation will be different since they are marked by a strongly heterogeneous porosity, which will lead to strong hysteresis effects; moreover, the swelling and shrinking properties of these soils will effect a change of the geometry of the porosity, which in its turn, may cause a shift or changes of the shape of the pF-curves. This will especially apply to the saline-alkaline subsoil of the GS III profile. The data obtained from the clayey flank soils are therefore representative for one special situation only.

In the above discussion the moisture availability of the 3 Girtasho profiles was compared on the basis of equally moistened soils. Under natural conditions, the moistening of the profiles at various depths will depend on a number of partially interrelated factors such as total rainfall, rainfall intensity, run-off, infiltration characteristics of the surface layer and deeper layers,rate of

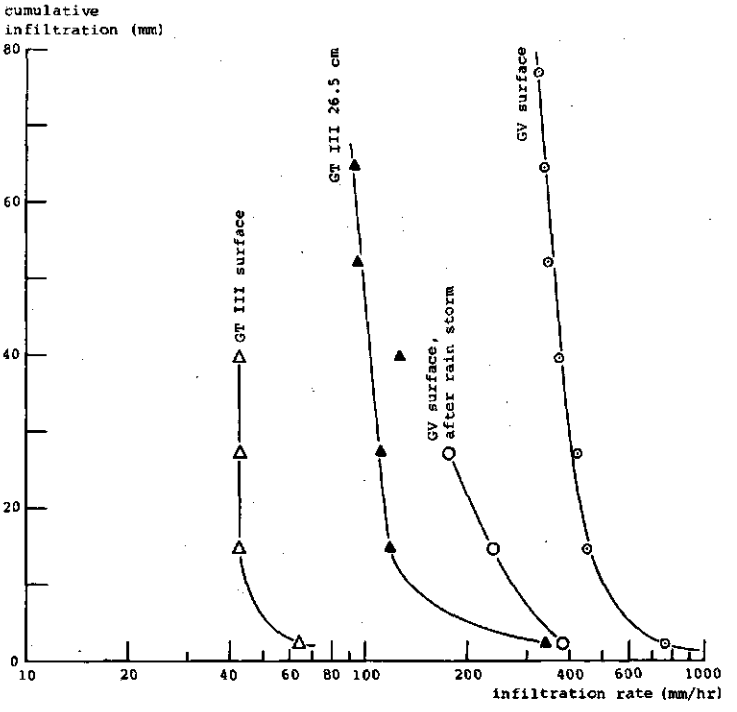
evapotranspiration. On the basis of these factors one may expect considerable differences in the actual amounts of stored water. The surface capping effects on the infiltration of rain water and run-off for the GT III and GS III profiles and the poor permeability (for both water and roots) of the natric horizon in the GS III profile seem most important. The GL II profile (tall grass spot!) seems in these respects the most favourable.
The factor infiltration will be dealt with in the next paragraph.

- Infiltration

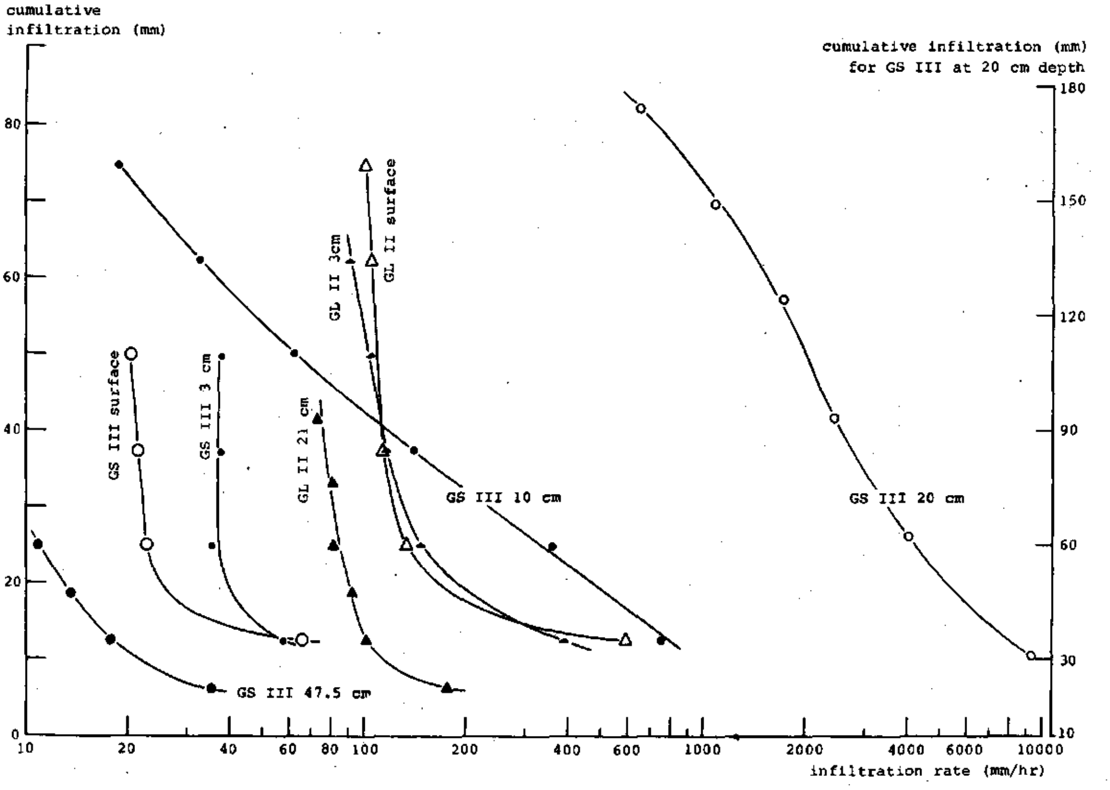
Data from infiltration experiments in the Girtasho profiles have been summarized in Appendix 36. The infiltration characteristics - showing the relationship between infiltration rates (mm/h) and accumulated amounts of millimeters of water infiltrated - are outlined in Fig. 33.

In the ridge top (GT III) profile, which supported a sparse cover of fairly short tufted grasses, the infiltration rates had become constant after about 25 mm had infiltrated, indicating a high stability of the soil structure and porosity. The surface values were over 2 times lower than the rate measured at a depth of 26 cm, due to the presence of a surface crust ("surface capping" effect). The surface soil of the solodized solonetz on the flanks (GS III, short grass spot) had much in common with the GT III top layer (see Morphology); infiltration rates had also become constant after 25 mm of infiltration,but the rate was about 2 times lower, probably due to a higher density (lower porosity) of the GS III surface soil. The "surface capping" effect for this layer is shown by comparing the infiltration curves found for the surface and at 3 cm depth: The infiltration rate in the saturated soil at 3 cm depth exceeded the rate measured for the surface 1,5-2 times.

Fig.33: Soil landscape I.3 (Long grasslands): Mean infiltration rates as related to total amounts of millimetres water infiltrated, for 4 characteristic profiles, measured at various depths; infiltration rings pushed into the soil by car jack.



a: GT III (ridge top, Girtasho area, near Simba kopjes) and GV (valley bottom, Girtasho area; near Simba kopjes).



b: GS III (flank, Girtasho area, short grass spot)and GL II(flank, Girtasho area, long grass spot).

A quite different picture show the data obtained from the natric horizon in the same profile (10, 20 and 47,5 cm depth). The experiment at 20 cm depth was carried out in an almost dry soil (actual moisture content near the permanent wilting point) and an extremely high permeability was found due to the numerous cracks - up to 3 mm wide - that occurred between the columnar elements and blocky substructures. Nevertheless there was a marked and continuous decrease during prolonged infiltration (GS III - 20 cm curve, vertical scale has been reduced twice). A much stronger reduction of the infiltration rate - by a two times lower amount of accumulated infiltration - was found when the soil was moistened before the experiment was done (10 mm of water two days, and another 5 mm one hour before the experiment took place); in this way the GS III-10 cm characteristic was obtained. This strong decrease of the infiltration rate was caused by the swelling of the soil aggregates: high clay contents and high percentages of exchangeable sodium. Under natural conditions the effects of the swelling on the permeability appeared even stronger: in the wet season the natric horizon readily forms an impermeable layer, which leads to a soaked surface horizon and to run-off during heavy rainstorms (almost no rainwater will penetrate into the soil). At lower depth (47,5 cm) a similar decrease of permeability was found: after 25 mm had infiltrated into the dry soil, the permeability had decreased to appr. 10 mm/h. A different situation was found for the GL II (tall grass spot) profile: after 25 mm had infiltrated the permeability had more or less stabilized at - still - fairly high rates at all depths investigated. A surface cap-effect as found for the GS III surface layer did not occur. Because the soil aggregates in the GL II

profile are more stable than in the solodized solonetz - because of the higher amounts of exchangeable calcium and the very low percentages of exchangeable sodium, see 2.3.1.4: Chemical characteristics - the effects on the permeability caused by swelling were smaller. The permeability inside the very coarse prismatic structures at lower depth (52-55 cm) was slow: most of the water, however, will move further downwards through and along the cracks that exist between the prisms.
From the valley bottom profile (GV, vertisol) experiments were carried out in the surface layer only. The permeability of the dry soil was very rapid in comparison with the infiltration rate measured in the surface soil of another vertisol, viz. the NaNo-S profile, that formed part of a toposequence in the Andropogon greenwayi grasslands. This high permeability, which decreases only slowly under saturated conditions, can be explained by the high porosity (bulk density 0.68 g/cm^3) and the high stability of the fine soil aggregates (granules).
At the end, the GV experiment was interrupted by a heavy rainstorm. After the rain had stopped, measurements were made on 6 untouched rings (experiments I′- II′- III′); 2 other rings could not be used because they had water standing in them. Now, there was a more rapid decrease of the permeability which may have been caused by an increased decay of the soil aggregates by the impact of the rain drops, probably in combination with the swelling of the soil surrounding the rings, which might have affected the porosity below and around the infiltration rings.
It is clear that the water absorbing capacities of the soils discussed above will have consequences with regard to the water storage in these profiles. On the ridge top run-off will not occur

below rainfall intensities of appr. 40 mm/hr; in this respect the ridge top soils with their relatively short grasses (clumps!) closely resemble the soils of the Short grasslands (compare Fig. 14, p.106) and also some soils of the Andropogon greenwayi grasslands, e.g. the profiles covered by a sparse vegetation (e.g. Digitaria macroblephara spots).

On the flanks, the situation will be different as well for the short grass as for the tall grass spots: at the short spots, run-off will already start at moderate rainfall intensities (appr. 20 mm/h) after the natric horizon, that is found in these profiles, has been moistened for some time. Since the natric horizon will form an almost impermeable layer, the possibilities for water storage will be largely restricted to the thin loamy surface layer, which is confirmed by the dense, shallow rooting system found in the GS III profile.

The surface horizon of the "tall grass" profile, at the other hand, has approximately a five times higher absorption capacity by which these profiles will mostly collect all the rainwater - the impact effects of the raindrops will be diminished by the high total cover of the tall grasses - and, probably, a considerable proportion of the run-off as well. The higher storage capacity of the "tall grass" profile is demonstrated by the deep rooting systems of the grasses in this soil.

Actual wateravailability in the 2 types of soils on the flanks will therefore depend on the infiltration characteristics rather than on the trajects of available moisture (mm at pF 2,0 or 2,5 - mm at pF 4,2).

During the wet season, also the profiles under the "short grass" will finally be moistened throughout; the moisture may be supplied partially by subsurface transport from the ridge towards the valley

- namely through the more permeable C-horizon material.
The valley bottom profiles will be water logged or even flooded during wet periods. When the soils start drying up, the plant growth will depend on a limited amount of available water since the availability trajects in these heavy clayey soils are narrow; some additional supply from temporary groundwater may be possible as long as the soil is not cracked.
The strong differences in permeability found for the soils of the Long grasslands (I.3) - as well between profiles of different relief positions within a catena as within one profile - are illustrative for the advanced stage of horizon differentiation in this area. Infiltration characteristics of Short grassland soils (I.2), which show only a weak horizon differentiation, show little differences; the ones obtained from the <u>Andropogon greenwayi</u> grasslands are intermediate between those of the Short and Long grassland soils.

2.3.1.4. Chemical characteristics

The selection of the profiles to be investigated on their chemical properties was made in close connection with the marked differences in profile development that had been observed between soils of different relief positions within a catena: especially between soil of the ridges and soils of the flanks. In addition important vegetational differences within the various soil units distinguished have been taken into account; in this respect much attention was paid to the mosaic of tall and short grass spots that occur on most of the flanks within the Long grassland area.

- Salinity and alkalinity

Salinity ($EC_e > 4$ mmhos/cm) and alkalinity (pH > 7.0, high amounts of exchangeable sodium) occurred widespread throughout the Long grasslands. Both external and internal salinization were found.

- External salinization

External salinization and very strong alkalinity were found in some ridge top and upper flank soils in the eastern parts adjacent to the Short grasslands, namely along scarps and "erosion steps" and around waterholes and other depressions (e.g. slick spots). In App. 37 and Fig.34c the salt distribution throughout a profile at a bare spot near the base of a scarp is shown; the profile (Simba-east erosion scarp) was located along the Gol track near the top of a ridge appr. 5 km east of the main road. The spot had a "puffed" surface layer; the highest salt concentration occurred just below the surface. The salt composition was marked by the dominance of sodium chloride and sodium sulphate; potassium amounted to over 10% of the sum of cations; on the anion side, free carbonate ranged from 7% near the surface to 15% at 50 cm, causing very high pH-values of over 10.0. The external salinization did probably originate by subsurface transport of salts leached from the scarp towards the bare depression at its base; groundwater did not play any role since a permanent watertable was lacking. The phenomenon of puffed surface layers has been described by Buringh (1960) and Driessen (1970): disruption of the soil aggregates by needle-shaped $Na_2SO_4.10\ H_2O$ crystalls caused the loose consistence. In view of the large quantities of sodium sulphate that were found, the above process has probably also taken place in the erosion scarp profile. The loose surface will be very sensitive to wind erosion, especially in case the soil is disturbed, e.g. by animals; this could be one of the mechanisms that causes or maintains the so-called "step" erosion (Ch. 3 : Special features).

Other places, affected by external salinization, are found in the alluvial deposits (riverbeds) of the Seronera River, the Oltuka and Loiyangalani River (both are tributaries of the Mbalageti River) and the Esoit Ndiakarta River; these areas will be discussed under Miscellaneous landtypes.

- Internal salinization

Internal salinization occurred widespread throughout the Long grassland, namely on ridge tops and on the flanks. In a ridge top about 5 km north of the erosion scarp profile, the Simba-east site is found; the site was covered by relatively short tufted grasses. Chemical data are found in App. 37 . The salt distribution forms a typical example of an internal solonchak in which the thickness of the salt-free top soil depends on the ratio between rainfall and evapotranspiration. The soil was strongly saline and very strongly alkaline below 40 cm, a situation comparable with the salinity patterns further eastwards (Short grasslands, e.g.

BARSEK profile). The salt distribution was marked by high amounts of soluble potassium in the saline parts of the profile (besides the dominance of sodium): 29% (above) to 23% (below) of the sum of cations, which is higher than what was found in any of the Short grassland profiles. Chloride and sulphate were the dominant anions, while in the strongly saline parts soluble carbonate+ bicarbonate varied between 25 and 30% of the total of anions, which is significantly lower than the percentages found in strongly saline soils of the Short grasslands.

In the Ngare Nanyuki ridge top profile (for data see App. 37) salinity increased less abruptly with depth: strongly saline below 80 cm and very strongly alkaline below 60 cm; the percentages of soluble K^+ were over 30% in most parts; in the saline subsoil soluble carbonate and bicarbonate amounted over 50% of the total of anions (comparable with the situation in the Short grasslands). The Ngare Nanyuki valley profile, which was located in open <u>Acacia</u> <u>torilis</u> woodland south-west of the Ngare Nanyuki ridge top, showed a toally different picture: the soil was non-saline and pH values were low within the upper 100 cm, which can be explained by the increased leaching inherent to the profile's relief position.

Many data were obtained from the Girtasho sequence which was situated farther from the boundary between the Long and Short grasslands than the profiles just described.

The sequence included 7 ridge top profiles (GT I-VII), 5 profiles on the flank, as well in short grass spots (GS I-III) as in tall grass spots (GL I, II), and 1 profile in the valley bottom unit (GV). In Table 25 and Fig. 34 data from 5 of the above profiles (GT II; GS I, III, GL II; GV) have been given.

Table 25: chemical data Girtasho sequence

G.T. II (ridge top)

depth (cm)	SP	pH_p	pH_e	EC_e	Na^+	K^+	Ca^{2+}	$Ca+Mg^{2+}$	Sum+	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Sum -	% Lime
						(all in meq/l of the sat. extracts)										
0- 10	58.3	6.70	8.08	0.89	1.03	3.61	2.65	4.17	8.81	-	5.33	0.97	0.52	-	6.82	0.57
10- 20	56.8	6.48	7.96	0.83	1.27	3.73	1.96	2.21	7.21	-	3.39	2.04	0.96	-	6.39	
20- 30	52.6	6.65	8.11	1.22	1.96	4.80	2.00	3.26	10.02	-	4.01	4.62	0.82	-	9.45	0.32
30- 40	45.5	7.03	8.02	4.70	9.13	18.34	6.55	14.06	41.53	-	2.97	36.42	1.15	-	40.54	0.65
40- 50	40.8	8.26	8.48	18.10	84.35	88.08	4.91	14.52	186.95	-	7.37	102.14	71.94	-	181.45	1.03
50- 60	39.3	9.82	9.84	24.70	134.79	136.26	0.52	0.52	271.57	50.63	41.71	82.88	96.88	-	272.10	3.32
60- 70	41.4	10.00	10.00	24.60	140.83	134.27	-	-	275.15	64.74	40.46	74.55	91.05	2.00	272.80	5.55
70- 80	41.7	9.95	9.94	25.00	144.35	135.96	-	-	280.31	65.15	46.79	73.95	89.81	3.00	278.70	8.48
80- 90	40.8	10.03	10.01	26.90	157.40	146.08	-	-	303.48	76.36	48.35	79.77	93.54	5.25	303.27	15.80
90-100	37.7	10.06	10.04	29.00	174.79	160.82	-	0.20	335.61	82.17	47.20	89.00	102.23	6.25	326.85	21.76

G.S. III (flank, "short grass" spot)

depth (cm)	SP	pH_p	pH_e	EC_e	Na^+	K^+	Ca^{2+}	$Ca+Mg^{2+}$	Sum+	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Sum -	% Lime (GS I)
0- 9	44.2	6.75	8.15	0.60	4.26	1.09	1.00	1.60	6.95							0.10
9- 20	76.0	6.94	8.50	0.90	9.17	0.66	0.59	0.65	10.48							0.00
20- 30	80.1	7.54	8.86	1.21	12.78	0.73	0.55	0.61	14.12							0.00
40- 50	79.7	8.04	8.80	1.81	17.39	1.14	0.54	0.54	19.07							1.07
60- 70	73.5	7.99	8.57	4.50	42.61	1.27		1.35	45.23		4.46			0.25		0.76
80- 90	67.0	7.93	8.42	7.30	64.35	3.07	1.77	2.63	70.05		3.74			0.00		0.84
100-110	61.2	7.93	8.38	8.90	87.83	2.88		4.18	90.89		3.29			0.25		1.61
120-130	63.5	7.87	8.32	9.40	82.61	3.30		5.53	91.44		3.19			0.50		1.94
140-150	55.7	8.02	8.40	8.50	80.43	3.15		5.03	88.61		5.56			1.50		7.77

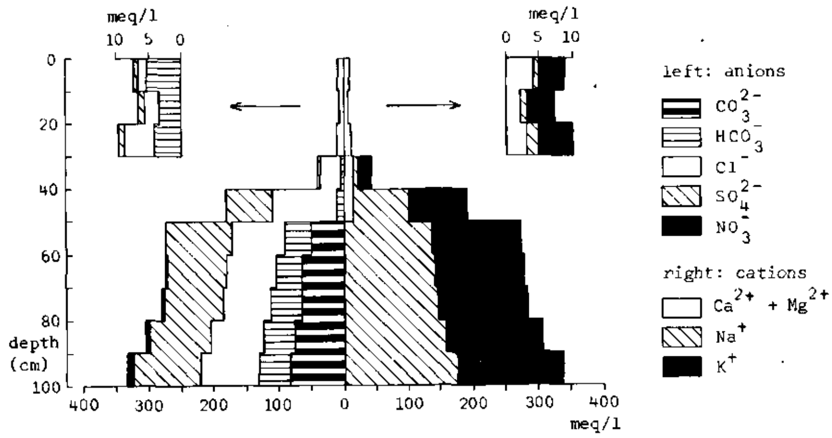
G.L. II (flank, "tall grass" spot)

depth (cm)	SP	pH_p	pH_e	EC_e	Na^+	K^+	Ca^{2+}	$Ca+Mg^{2+}$	Sum+	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Sum -	% Lime (GL I)
0- 10	61.8	6.67	7.91	1.00	1.00	2.39	4.82	7.56	11.05		3.02			-		0.12
10- 20	63.5	6.22	7.70	1.05	1.29	2.31		8.03	11.63		4.73			-		0.15
20- 30	69.7	6.16	7.33	0.78	1.19	1.77	3.94	5.63	8.59		3.36			-		0.07
40- 50	70.0	6.26	7.59	0.47	1.08	1.02	2.38	3.07	5.17		1.92			-		0.18
60- 70	71.6	6.50	7.90	0.42	1.38	0.78		2.40	4.56		1.68			-		0.28
80- 90	67.4	6.84	8.24	0.37	1.68	0.63	1.29	1.65	3.96		2.21			-		0.38
100-110	62.3	7.10	8.42	0.39	1.95	0.64		1.41	4.00		2.42			-		0.35
120-130	55.4	7.51	8.55	0.48	2.50	0.84		1.85	5.19		3.53			-		2.40
140-150	53.1	7.62	8.65	0.58	3.30	1.08		1.92	6.30		3.81			-		3.58

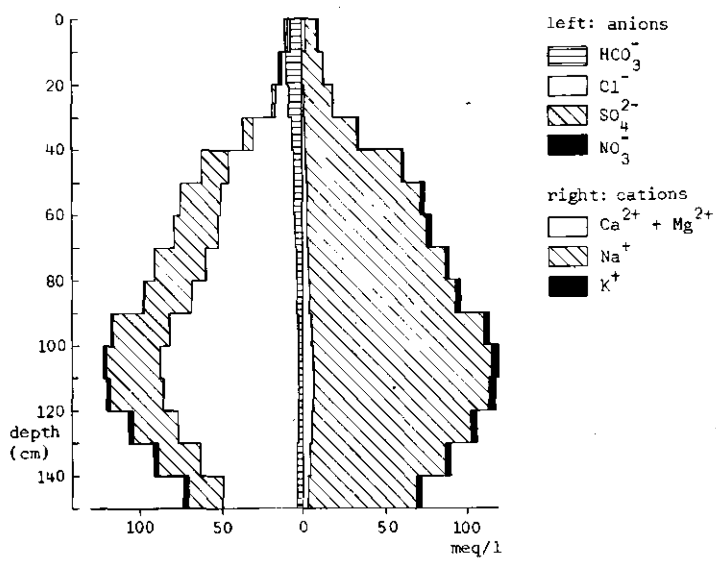
G.V. (valley bottom)

depth (cm)	SP	pH_p	pH_e	EC_e	Na^+	K^+	Ca^{2+}	$Ca+Mg^{2+}$	Sum+	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Sum -	% Lime
0- 10	85.1	6.01	8.02	0.50	1.47	1.07	1.75	2.66	5.20		2.56			-		0.28
10- 20	80.5	6.01	7.70	0.33	1.18	0.66		1.46	3.30		1.45			-		0.41
20- 30	80.8	5.91	7.93	0.27	1.04	0.55	0.92	1.22	2.81		1.52			-		0.47
40- 50	80.7	6.04	7.89	0.24	0.99	0.50	0.75	1.08	2.57		1.52			-		0.23
60- 70	83.1	6.20	7.80	0.21	0.87	0.39		0.95	2.21		1.11			-		0.23
80- 90	86.6	6.30	7.81	0.22	1.03	0.31	0.61	0.85	2.19		1.45			-		0.16
100-110	82.1	6.60	7.93	0.26	1.09	0.31		1.15	2.55		1.14			-		0.00
128-140	71.3	7.47	8.43	0.43	1.52	0.38	2.15	2.57	4.47		2.77			-		3.17

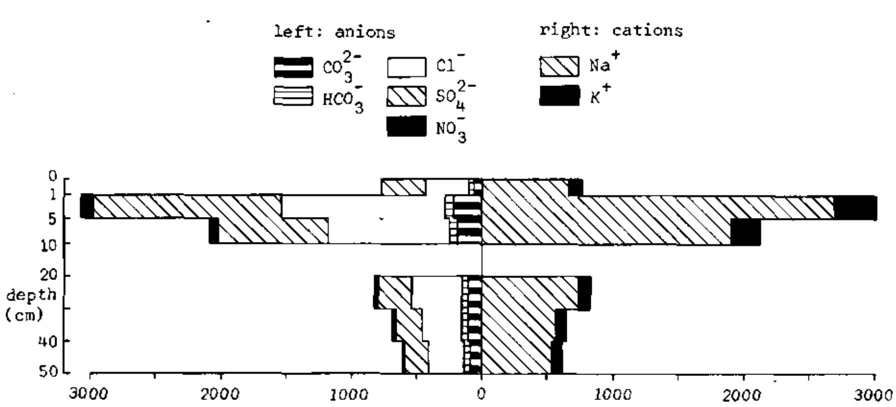
Fig.34: Salinity patterns and salt composition in 3 profiles of different relief positions within soil landscape I.3 (Long grasslands): ion concentrations in milliequivalents per litre of the saturation extracts.



a: GT II (ridge top near Simba kopjes).



b: GS I (flank, near Simba kopjes, "short grass" spot).



c: Simba east erosion scarp (ridge top, bare spot near the basis of a low scarp, south of the Simba east rain gauge, close by the Gol track).

The ridge top profile GT II was strongly saline and very strongly alkaline below 40-50 cm; the salt composition has been outlined graphically in Fig. 34 . Most striking again were the very high amounts of soluble potassium; in the non-saline and slightly saline top soil K^+ was even the dominant cation, while in the strongly saline-alkaline parts (below 40 cm) the amounts of soluble K still equalled those of Na.

In the top 50 cm also Ca^{2+} and Mg^{2+} were important; the amounts, found between 30 and 50 cm, and especially those of magnesium, were unusually high (higher solubility of Ca and Mg due to relatively high amounts of Cl^- and SO_4^{2-}?). On the anion side Cl^- and SO_4^{2-} were dominant over CO_3^{2-} and HCO_3^- except for the top 20 cm; the highest percentage of chloride was found in the upper layer of the salt affected part of the profile.

Also the other ridge top profiles (GT I, III-VII) were found to be saline ($EC_e > 4$ mmhos/cm) within a depth of 1.0 metre. Between the profiles there were large differences in salt concentration: 4 mmhos/cm in GT VII to 34 mmhos/cm in the GT V profile (App. 38[1]). Variations in alkalinity were less strong; in most profiles pH-values of over 10.0 were recorded. In the deeper layers of the GT II and GT V profiles some free nitrate was found. Differences in salinity in the subsoils of the ridge profiles seemed to coincide with differences in botanical composition of the grass vegetation. The latter stood out most clearly in case of the GT VII profile, in which the lowest degree of salinization was found; the profile was located in a small, isolated, almost pure stand of _Digitaria scalarum_. This vegetation type was by no means representative for the rest of the grassland on the ridge top (mainly consisting of _Digitaria macroblephara_ and _Cynodon dactylon_); The salinity pattern in the GT VII profile seems therefore not very representative as well.

Halfway down the slope the GS and the GL profiles were found; they were situated respectively in "short" grass spots with <u>Digitaria macroblephara</u>, <u>Microchloa kunthii</u>, <u>Eustachys paspaloïdes</u> as the dominant species, and in the "tall" grass spots, in which grasses like <u>Themeda triandra</u> and <u>Pennisetum mezianum</u> were dominant. Short and tall spots formed mosaics. Besides the chemical data from the GS III and GL II profiles, shown in Table 25, also figures from the nearby GS I and GL I profiles have been given (Appendix 39). The profiles in the tall grass spots (GL I,II) were found to be non-saline throughout (0-1 50 cm); highest conductivities of the saturation extracts (1 mmho/cm) occurred near the surface. Soil reaction (saturated paste) changed gradually from slightly acid near the surface to mildly alkaline below.

In the top 60-70 cm, Ca^{2+} and Mg^{2+} were the dominant cations in the soil solution; below this depth Na was found to increase gradually with the depth. Dominant anions in the top 60-70 cm were Cl^- and SO_4^{2-}; below this depth, however, it was HCO_3^-. In the GL I profile HCO_3^- was the dominant anion throughout the profile. The "short grass" spot profiles (GS I,II and III) were internally salt affected; the highest salt concentrations occurred below 100 cm (moderately saline soil). Throughout these profiles Na^+ was the dominant cation and Cl^- the dominant anion except for the top 20(30)cm - i.e. the loamy surface layer and the upper part of the columnar B-horizon -, in which case it was HCO_3^-; also sulphate was important. The amounts of Ca^{2+} and Mg^{2+} increased gradually with the depth, following the salinity pattern (high amounts of chlorides and sulphates!) The salinization pattern in the GS I profile is shown in Fig. 34. Free nitrate occurred both in the GS I and III profiles (GS II was not checked for nitrate) below a depth of 70 cm. Soil reaction was neutral in the surface layer and moderately alkaline below 20-30 cm. In the discussions preceding the chemical properties, the "short grass" spot profile has been qualified several times as a "solodized solonetz". Considering the pH ranges for A and B-horizons and the salt distribution in the profile, that have been given in the Soil Survey Manual for this type of soil, the name fits very well. For the Girtasho "short grass" spot profiles, however, it is a question whether they are the product of a degradation of a true solonetz (solodization). If the solodized solonetz would form only after "considerable time" (SSM), the GS profiles would be in the stage of solodization. In view of the rapid changes that may take place in the chemical status of the soils, mainly as a result of termite activity, the solodization process might readily be restored into a solonizing one; for this reason solodized and solonized profiles are likely to occur side by side. More attention to the chemical aspects of this problem is paid in the discussion on the origin of the short and tall grass spots in the chapter on special features.

The low salt contents in the "tall grass" profiles on the flanks are very likely the result of intensive leaching processes during wet periods. Besides the rainfall, also run-off from the short grass spots (low soil cover of the vegetation!) collects in the tall grass profiles; penetration to lower depths is favoured by the high permeability (see infiltration) and by wide cracks that run down to a depth of 1 metre or more. Excesses of soil moisture will drain off rapidly: the soil pits (GL I and II) remained dry during the wet season, while there was hardly any collapse of the soil structure along their walls (stable structure!). Nearly the opposite occurred in the "short grass"

profiles: during wet periods leaching becomes strongly reduced soon because of the impermeability of the natric horizon; salts that have accumulated in the subsoil will remain there. The internal drainage proved to be poor: soil pits remained full of water during the wet season due to the swelling of the surrounding soil and the formation of an impermeable layer of dispersed clay from the B-horizon at the bottom of the pit.
Moisture tests made during wet periods showed that the "tall grass" spots were moist down to the C-horizon, while in the "short grass" spots only the A- and upper part of the B-horizon were moist.

The valley bottom profile was non-saline throughout. Soil reaction varied between moderately/slightly acid near the surface to neutral/ mildly alkaline in the C-horizon. Ca^{2+} and Mg^{2+} amounted half of the sum of the cations; the Na^{+} contents exceeded those of K^{+} by a factor 2 to 3. The very low conductivities are related with the strong leaching processes in these soils: comparable with the situation in the "tall grass" spots; the amounts of run-off can be expected to be much higher.

Another sequence was located near the centre of the Long grasslands: the Sersi (Seronera-Simba) site. It included several ridge top profiles (Sersi 1, 2 and 3), a "short grass" spot profile (Sersi 4) and a "tall grass" spot profile (Sersi 5) on the upper flank, and 2 profiles in an active termite mound (TH 1 and TH 2), also on the upper flank; all data on chemical status of the above profiles have been listed in Appendix 40[1].
The three ridge top profiles were all non-saline ($EC_e < 4$ mmhos/cm)

[1] available at the Dept. of Tropical Soil Science, Agricultural University, Wageningen, Holland.

above the petrocalcic horizon, which occurred at a depth of 1 metre, but there was a clear increase of the conductivity with increasing depth. Soil reaction changed from slightly acid near the surface to moderately alkaline just above the petrocalcic horizon. In all profiles K^+ was the dominant cation in the soil solution, HCO_3^- the domiant anion.

Whereas there were considerable differences in salinity and alkalinity between the Sersi and Girtasho ridge top soils, the upper flank profiles at Sersi (Sersi 4 and Sersi 5), however, gave pictures that were very similar to those obtained from corresponding situations on the flanks in the Girtasho area.

In the termite hill profiles (TH 1 and TH 2) - the mound was situated inside a short grass area appr. 60 m from the Sersi 4 profile - the pH of the surface layer was higher than in the nearby "short" and "tall grass" soils. In the TH 1 profile (in the mound) also the conductivity of the surface soil was higher; strikingly high were the amounts of free nitrate. The location of the termite mound - c.q. surrounded by the so-called "short grass" grassland type - as well as the chemical data (nitrate content!), gave the indication that also in the Long grasslands termite activity played an important role in the salinization process (see also 2.2., Soil Landscape I.2: Andropogon greenwayi grasslands).

Two ridge top profiles were selected close near the boundary between the Long grasslands and the woodlands of the dissected plain: Sametu-north 1 & 2 (SAMN 1,2). Profile 1 supported a fairly short dense stand of mainly Digitaria macroblephara, profile 2 was situated in an isolated spot of tall grasses of which Pennisetum mezianum was by far the sominant species.

Both profiles were non-saline to a depth of 120 cm. Conductivity and pH values increased with depth in both profiles; the strongest increases were found in the profile 1 (i.e. under the short grass type). The occurrence of lower conductivities under isolated <u>Pennisetum mezianum</u> patches had also been found in the adjacent A 4 area of the Short grasslands.

Soluble potassium exceeded the amounts of sodium in the upper half of the profiles; in the lower half the opposite was found. Ca^{2+} + Mg^{2+} were the dominant cations in the saturation extract of the tall grass spot profile (SAM N 1,2; data in App. 41).

Some 5 km southwards, two lower flank profiles have been investigated: Sametu Kopjes 1 (taller grasses, high cover) and 2 (very short grass, very low cover); chemical data have been given in App. 41 . The profile covered by the taller grasses was non-saline throughout; the "short grass" profile was slightly saline below 70 cm and strongly saline below 90 cm; alkalinity was slightly higher in the salt-affected profile. In the greater part of the non-saline profile (SAM K 1) as well as in the non-saline part of the "short grass" profile (SAM K 2), K^+ was the most important cation in the soil solution; at increasing EC_e-values Na^+ became dominant. In the "short grass" profile very high concentrations of Ca^{2+} and Mg^{2+} were found between 90 and 120 cm; on the anion side chloride was the dominant ion. It should also be noticed that in the soil extracts from the "tall grass" profile the amounts of Ca^{2+} did exceed those of Mg^{2+} 3-5 times in most parts, whereas in the "short grass" profile - also in the non-saline parts - this was less than 2 times, while below 90 cm Mg^{2+} even exceeded Ca^{2+}. The relatively high magnesium concentrations in the short grass spot profile seem rather exceptional and may be related with ancient or recent (Masai!) human activity (at the site many artefacts were found).

The chemical status of the profiles at the "Lolick site", some 11 km south-east of the Serengeti Research Institute (data given in App. 41), was similar to those of the Sametu-north ridge top profiles. Conductivities in the Loliok profiles were somewhat higher; highest conductivities were found again in the profile that supported shorter grasses (<u>Digitaria</u> <u>macroblephara</u> a.o.). Potassium was the dominant cation in the soil solution: except for the top 20 cm, K^{+} amounted over 50% of the sum of cations; chloride and sulphate were dominant over bicarbonate.

Further towards the west, appr. 2,5 km south of the crossing of the Seronera River and the main road, a number of sites was selected between the top of a ridge and the boundary between ridge- and upper flank soils: Serzu sites (Serzu = Seronera south) the selection of the profiles was largely based on vegetational differences. Results have been given in Appendix 42[1].
The ridge top soil's characteristics (Serzu 1) were very similar to those of the Sersi ridge top profiles, except for the lime contents which were lower (higher rainfall, see Fig. 6!).
Towards the flanks a differentiation in the distribution pattern of the free salts was observed. Serzu 2 lay near the base of a very recent termite mound; the site was colonized by tall <u>Cynodon</u> <u>dactylon</u>, which fact could be observed in most disturbed soils (see Part III: Vegetation and Soils); accumulation of salts had not (yet?) taken place. Between Serzu 3 and 4 (tall resp. short grass spots) differences were small, but a marked accumulation of free salts was found in the lower parts of the Serzu 5 profile. The latter profile was situated in a perfectly circular spot, sparsely covered by very short grasses, which looked very much like a leveled old termite mound; the high amounts of free nitrate and low Ca^{2+}/Mg^{2+}

(soluble) ratios below 80 cm support this idea. Further from the ridge top the chemical differences between "tall grass" and "short grass" profiles had become more pronounced: Serzu 6 and 7, of which the Serzu 7 profile was a typical solodized solonetz; this situation corresponded well with the data obtained from the Sersi and Girtasho sequences. Throughout the transect, the percentages soluble potassium - as related to the total of cations - were found to decrease down the slope; similar trends were also found in the Sersi and Girtasho sequences. At the end of this paragraph there will be some special remarks on the potassium status of the Long grassland soils.

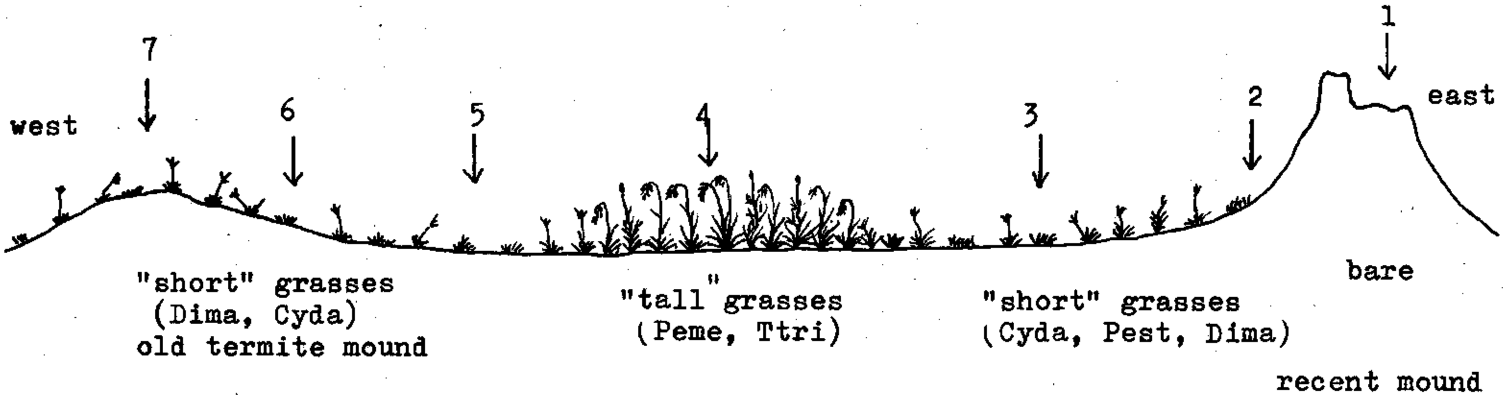
Table 26 shows the data obtained from a 20 m transect through short and tall grass spots on a ridge along the mainroad some 12,5 km south-east of Seronera; the transect consisted of 7 profiles and included two termite mounds: a recent one (profile 1) and an old one (profile 7).

Profile 1 - which was difficult to sample because of the many holes inside the mound - and profile 7 had SP-values (moisture percentages of saturated pastes) of 50% or higher throughout, whereas in the other profiles the SP-values of the toplayers were consistently lower - and lower than 50% - than those of the subsoil (comparable with Girtasho, Sersi and Serzu flank profiles); evidently the termites had used finer textured material for the building of the mound. The termite mound profiles (1 and 7) also had considerably higher pH-values and conductivities. In the recent mound (profile 1) the salinization pattern was irregular, while in the old mound (profile 7) salinity increased gradually with the depth to moderately saline at 60-80 cm. All other profiles were non-saline and weakly acid near the surface to mildly alkaline at

Table 26:

Soil Landscape I.3 (Long grasslands): termite mound transect on a ridge, 12.5 km SSE of Seronera.

Profile	depths (cm)	SP	pH_p	pH_e	EC_e	NO_3^- (meq/l)
1	0-20	52.6	7.64	8.27	0.90	3.0
	20-40	52.8	7.32	7.70	5.10	15.0
	40-60	50.1	7.48	7.97	1.72	1.5
2	0-20	41.8	7.51	8.38	0.52	2.5
	20-40	46.9	7.65	8.22	0.65	2.5
	40-60	44.5	7.24	7.96	1.20	7.5
	60-80	46.8	7.20	7.94	1.25	7.5
	80-100	53.9	7.23	7.98	2.00	12.5
	100-120	53.3	7.05	7.60	3.90	15.0
3	0-20	40.5	6.15	7.45	0.70	4.5
	20-40	48.0	6.22	7.68	0.33	0.25
	40-60	52.1	6.53	7.63	0.39	-
	60-80	55.0	6.98	7.83	0.43	2.5
	80-100	52.7	7.31	7.93	0.87	4.5
4	0-20	44.2	6.23	7.18	0.65	-
	20-40	52.8	6.15	7.60	0.24	-
	40-60	62.6	6.65	7.99	0.29	-
	60-80	58.8	7.59	8.10	0.34	$\approx$0.0
	80-100	59.2	7.70	8.32	0.42	0.75
	100-120	54.4	7.88	8.30	0.46	2.0
5	0-20	43.6	6.32	7.37	0.36	-
	20-40	44.9	7.19	8.30	0.52	-
	40-60	53.9	7.10	8.30	0.47	-
	60-80	59.6	7.34	8.16	1.30	4.0
	80-100	58.3	7.51	8.10	1.75	10.0
	100-120	56.5	7.30	7.60	1.90	12.5
6	0-20	44.3	7.05	8.12	0.47	-
	20-40	49.6	6.70	7.92	0.38	-
	40-60	50.2	7.31	8.13	1.00	3.0
	60-80	50.6	7.30	8.13	1.26	7.5
	80-100	51.8	7.19	7.60	1.75	10.0
	100-120	57.8	7.71	8.00	2.62	15.0
7	0-20	52.7	7.50	8.33	0.52	-
	20-40	49.5	7.51	8.40	1.08	2.5
	40-60	60.4	7.40	7.92	4.10	12.5
	60-80	51.8	6.63?	6.91?	14.00	35.0



lower depth. Lowest conductivities occurred in profile 4 which was situated in a tall grass spot (with Themeda triandra, Pennisetum mezianum as dominant grass species). The conductivities increased both towards the old and the recent mound, by which the grass vegetation changed from the tall type with a high cover (over 75%) into a short type with a low cover (less than 50% ; dominant species in the latter case were Cynodon dactylon and Digitaria macroblephara).

It is clear that the salinization has spreaded or is still spreading from the mounds; the distribution of the free nitrate in the profiles supports this view. In the profiles 2 and 3 free nitrate occurs even in the surface soil; evidently it had been leached down recently from the fresh mound. In the profiles 4, 5 and 6, in which the free nitrate is likely to have come from the older mound, no nitrate was found in the surface layers, probably as a result of prolonged leaching by rainwater. The situation just described, confirms the findings from the termite mound transects in the Andropogon greenwayi grassland (NaNo transects, see Ch.3 : Special features).

With the help of the above findings the distribution of "short grass" and "tall grass" spots in the Long grasslands and the soil types associated with these vegetation types may be explained as follows: from a termite mound, originated in a tall grass spot (see profile description of the GL I profile , Appendix 31) - which seems likely because food supply under the tall grasses can be expected to be more favourable than under a sparse short grass vegetation -, salts (especially sodium salts) will spread around and Ca^{2+} and Mg^{2+} on the exchange complex in the surrounding soils will gradually be replaced by Na^{+}, resulting into increasingly unstable soil structures. During wet periods soil aggregates in the surface soil will become partly dispersed (degradation of soil structure); the dispersed clay particles will partly illuviate into the B-horizon. At first there will be a saline-alkali soil, but after the supply of salts from the termite mound has stopped - i.e. when the mound is not longer "active" - and leaching processes have become dominant, the prismatic structures of the B-horizon will become column-shaped as a result of the increased swelling and shrinking of the alkaline soil material upon wetting and drying. In dry periods soil material from the surface layer will collect in the cracks between the structural elements; upon wetting this will cause an extra pressure in upward direction. The above process will lead to the formation of a relatively coarse-textured surface layer overlying a heavy clayey columnar B-horizon (natric horizon); the heads of the colums may be coated with coarse sandgrains.

Under continuous leaching the surface layer will become acid and also the exchangeable sodium in the natric horizon will become gradually replaced by hydrogen, calcium and magnesium (weathering!): solodization process; the soil is then called a solodized solonetz. The solodizing process may be a long lasting process, during which the soil may change into a solod. There is, however, a good chance that this stage will never be reached in these soils because of the continuous chemical rejuvenation - i.e. supply of soluble salts - by weathering, by termite activity (from deeper soil layers) or by fresh ash deposits from the still active Crater Lengai; this may transform the soil into a saline-alkali soil again, after which another cycle will start: continuous process.

Essential for the above process is the relatively rapid supply of considerable amounts of soluble sodium in the surface soils in this part of the study area. De Mondésir (1888) and Gedroiz (1912)

(in E.W. Russell, 1961)
explained the formation of a solonetz by the gradual accumulation of carbonate and bicarbonate ions (via carbondioxyde from the plant roots and soil organisms), which are neutralized in the soil solution by sodium ions from the exchange complex (replacement by the other cations like hydrogene or calcium). This requires an initially high amount of exchangeable sodium, which will have been the case under saline or alkaline conditions, e.g. during the stage of external salinization caused by flooding or by capillary rise of groundwater with high SAR-values towards the soil surface (solonchak). The solodizing process will start after a lowering of the groundwater table by which salts are removed from the top soil by leaching processes (free drainage).
This type of salinization process is unlikely to occur or to have occurred in the Long grassland soils, since salinization of the top soil will not take place as a result of flooding or capillary rise as no groundwater table is found within the upper 2 metres; probably it is even absent. Only small amounts of salts might be supplied during the wet season from a temporary water table or by run-off. An adequate and more or less continuous supply of soluble salts towards the upper layers of the soil profiles can therefore only be explained by termite activity in combination with weathering and rejuvenation by ash deposits from Oldoinyo Lengai.

- CEC, exchangeable cations

Tables 27 and 28 show data obtained from the Girtasho area, namely from GS III (flank, short grass spot), GL II (flank, tall grass spot) and GV (valley bottom). The differences between the "short grass" and the "tall grass" profile were the following:

a. Higher CEC-values in the short grass profile below 20 cm,

Table 27: cation exchange capacity and exchangeable cations
in 2 Long graseland flank soils (GL II, GS III)

G.L.II (Girtasho, tall grass spot II)
CEC, ESP etc. (corrected) in meq/100 g

	CEC	Na^+	K^+	Ca^{2+}	Mg^{2+}	Total Bases	"H^+"
0-10	35.05	0.26	4.83	19.40	7.06	31.55	3.50
20-30	36.55	0.33	4.83	21.48	7.35	33.99	2.56
40-50	37.23	0.46	4.52	22.73	7.54	35.25	1.98
80-90	38.32	0.76	4.57	24.69	7.59	37.61	0.71

Percentages:

	CEC	% Na	% K	% Ca	% Mg	Base Sat.	% "H"
0-10	35.05	0.74	13.78	55.35	20.14	90.01	9.99
20-30	36.55	0.90	13.31	58.77	20.11	92.99	7.01
40-50	37.23	1.24	12.14	61.05	20.25	94.68	5.32
80-90	38.32	1.98	11.93	64.43	19.81	98.15	1.85

Exchangeable potassium percentage (EPP) estimated from the potassium adsorption ratio (PAR) versus the EPP from experiments (EPP - exp.)

	Ca + Mg^{2+} (meq/l)	K^+ (meq/l)	PAR	EPP	EPP-exp.
0-10	7.56	2.39	1.23	14.18	13.78
20-30	5.63	1.77	1.06	12.81	13.31
40-50	3.07	1.02	0.82	10.91	12.14
80-90	1.65	0.63	0.69	9.82	11.93

G.S.III (Girtasho, short grass spot III)
CEC, ESP etc. (corrected) in meq/100 g

	CEC	Na^+	K^+	Ca^{2+}	Mg^{2+}	Total Bases	"H^+"
0- 9	36.73	1.40	3.84	16.44	4.47	26.15	10.58
20-30	42.98	8.49	5.84	21.14	4.40	39.78	3.11
40-50	47.05	15.32	6.60	19.92	4.83	46.72	0.33
80-90	41.17	16.34	7.07	12.16	6.08	41.65	-

Percentages:

	CEC	% Na	% K	% Ca	% Mg	Base Sat.	% "H"
0- 9	36.73	3.81	10.45	44.76	12.17	71.19	19.81
20-30	42.98	19.75	13.59	49.19	10.24	92.77	7.23
40-50	47.05	32.56	14.03	42.34	10.37	99.30	0.70
80-90 1	41.17	39.69	17.17	29.54	14.77	101.17	-
2	41.65 (=101.17%)	39.23	16.97	29.20	14.60	100.00	-

Exchangeable potassium percentage (EPP) estimated from the potassium adsorption ratio (PAR) versus the EPP from experiments (EPP - exp.)

	Ca + Mg^{2+} (meq/l)	K^+ (meq/l)	PAR	EPP	EPP (exp.)
0- 9	1.60	1.09	1.22	14.10	10.45
20-30	0.61	0.73	1.32	14.89	13.59
40-50	0.54	1.14	2.19	21.05	14.03
80-90	2.63	3.07	2.68	24.09	16.97

Table 28 : cation exchange capacity and exchangeable cations in a Long grassland valley bottom soil (G.V.)

G.V. (Girtasho valley)

CEC, ESP etc. (corrected) in meq/100 g

	CEC	Na^+	K^+	Ca^{2+}	Mg^{2+}	Total Bases	"H^+"
0–10	47.55	0.51	5.82	25.40	9.04	44.77	6.78
20–30	44.84	0.56	5.05	26.11	8.59	40.31	4.53
40–50	44.02	0.65	4.72	26.82	8.77	40.96	3.06
80–90	42.39	0.69	4.29	28.36	7.18	40.52	1.87

Percentages:

	CEC (meq/100 g)	% Na	% K	% Ca	% Mg	Base Sat.	% "H"
0–10	47.55	1.07	12.24	53.42	10.01	85.74	14.26
20–30	44.84	1.25	11.26	58.23	19.16	89.90	10.10
40–50	44.02	1.48	10.72	60.93	19.92	93.05	6.95
80–90	42.39	1.63	10.12	66.90	16.94	95.59	4.41

Exchangeable potassium percentage (EPP) estimated from the potassium adsorption ratio (PAR) versus the EPP from experiments (EPP - exp.)

	Ca + Mg^{2+} (meq/l)	K^+ (meq/l)	PAR	EPP	EPP (exp.)
0–10	2.66	1.07	0.93	11.78	12.24
20–30	1.22	0.55	0.70	9.91	11.26
40–50	1.08	0.50	0.68	9.71	10.72
80–90	0.85	0.31	0.48	7.49	10.12

whereas the clay percentages (according to the analyses carried out by the Oosterbeek laboratory: pre-treatment with HCl!) were equal to (20-30) or even lower than those in the "tall spot" profile (see Table 22). In view of the low clay content - compared with that of the GL II profile - the CEC of the loamy top soil of the GS III profile was relatively high. Since amorphous material formed an important part of the total mineral fractions in both profiles the higher CEC values in the "short grass" profile (GS III) can be attributed to the higher pH-values of the soil material in this profile (CEC determinations not buffered; CEC values positively related with the pH, see Aomin and Jackson , 1959).

b. In both profiles the base saturation was less than 100%. The lowest value (still 80%!) was found in the loamy toplayer of the solodized solonetz (GS III); between 9 and 50 cm in this profile, the base saturation increased rapidly to 100%, while there was a slight oversaturation at 80-90 cm. In the surface soil of the "tall grass" profile the base saturation amounted 90%; although there was a gradual increase downwards, the base saturation was still less than 100% at 80-90 cm depth.

c. In the solodized solonetz (GS III) the monovalent cations formed an important part of the exchangeable bases below a depth of 20-30 cm; especially high were the amounts of adsorbed Na (saline-alkali soil); the potassium amounts increased together with the sodium percentage with depth, coinciding with increasing salinity and increasing amounts of soluble K. Opposite to the increase of the monovalent ions there was a decrease of the bivalent cations, namely of calcium (magnesium was rather constant).

In the "tall grass" profile the composition of the exchange complex was quite different. Bivalent ions were far dominant over the monovalent ions; there was even an increase of the relative amounts of Ca + Mg with the depth. The relative amount of adsorbed Mg was nearly twice the Mg-percentage in the short grass soil; the same applied to the Ca-percentages in the 80-90 cm layers. The amounts of adsorbed sodium were almost negligible, but the amounts of exchangeable potassium were important and were of the same order of magnitude as those in the GS III soil. Contrary to the situation in the GS III soil, there was a slight decrease of the K-percentage with increasing depth, coinciding with a decrease of the amounts of soluble K in the saturation extract.

The valley bottom soil (GV) had somewhat higher clay contents within the upper 1 metre than the flank soils, especially in the surface horizon; the CEC values were consequently higher than those found in the GL II profile and in the loamy surface layer of the solodized solonetz (GS III). The composition of the cations on the exchange complex of the GV soil was very similar to that of the "tall grass" profile on the flank.

For the three profiles, discussed above, Exchangeable Sodium Percentages (ESP) and Exchangeable Potassium Percentages (EPP) have been calculated from the Sodium and Potassium Adsorption Ratio's (SAR and PAR) according to the formulas given in the USDA Agricultural Handbook-60 (1954):

$$ESP = \frac{100\ (-0{,}0126 + 0{,}01475\ SAR)}{1 + (-0{,}0126 + 0{,}01475\ SAR)} \quad \text{and}$$

$$EPP = \frac{100\ (0{,}0360 + 0{,}1051\ PAR)}{1 + (0{,}0360 + 0{,}1051\ PAR)}$$

At low concentrations of Na in the saturation extracts (GL II,

Table 29 : Exchangeable Sodium Percentage (ESP) estimated from the Sodium Adsorption Ratios (SAR) versus the ESP from experiments (ESP-exp.)

A : Short grasslands

profile	depth(cm)	SAR	ESP	ESP-exp.
BARSEK	0-10	0.65	-0.30	2.18
	20-30	1.47	0.91	3.81
	40-50	233.00	77.40	64.80
	60-70	956,00	93.40	71.70
NaNae 2	0-20	1.05	0.29	2.08
	40-60	20.50	22.40	20.00
	80-100	507.00	88.20	63.70

B : <u>Andropogon greenwayi</u> (Intermediate) grasslands

profile	depth(cm)	SAR	ESP	ESP-exp.
NaNae 3	0-20	0.68	-0.26	1.37
	40-60	2.57	2.47	3.44
	80-100	10.60	12.60	12.60
Na-Lag	0-20	0.73	-0.18	1.65
	20-55	1.27	0.61	2.17
	55-75	4.07	4.53	5.27
	75-95	12.10	14.20	16.80

(B cont.)

profile	depth(cm)	SAR	ESP	ESP-exp.
NaNo-A	0-10	0.80	-0.08	0.77
	20-30	2.49	2.36	2.01
	40-50	16.60	18.80	9.75
	70-80	67.60	49.60	37.50
NaNo-B	0-10	0.91	0.08	1.38
	20-30	2.80	2.79	3.69
	40-50	38.30	35.60	22.80

C : Long grasslands

profile	depth(cm)	SAR	ESP	ESP-exp.
GL II	0-10	0.57	-0.43	0.74
	20-30	0.71	-0.21	0.90
	40-50	0.87	0.03	1.24
	80-90	1.85	1.45	1.98
GS III	0-9	4.76	5.45	3.81
	20-30	23.10	24.70	19.80
	40-50	33.50	32.50	32.60
	80-90	56.10	44.90	39.20
GV	0-10	1.27	0.62	1.07
	20-30	1.33	0.70	1.25
	40-50	1.35	0.72	1.48
	80-90	1.58	1.06	1.63

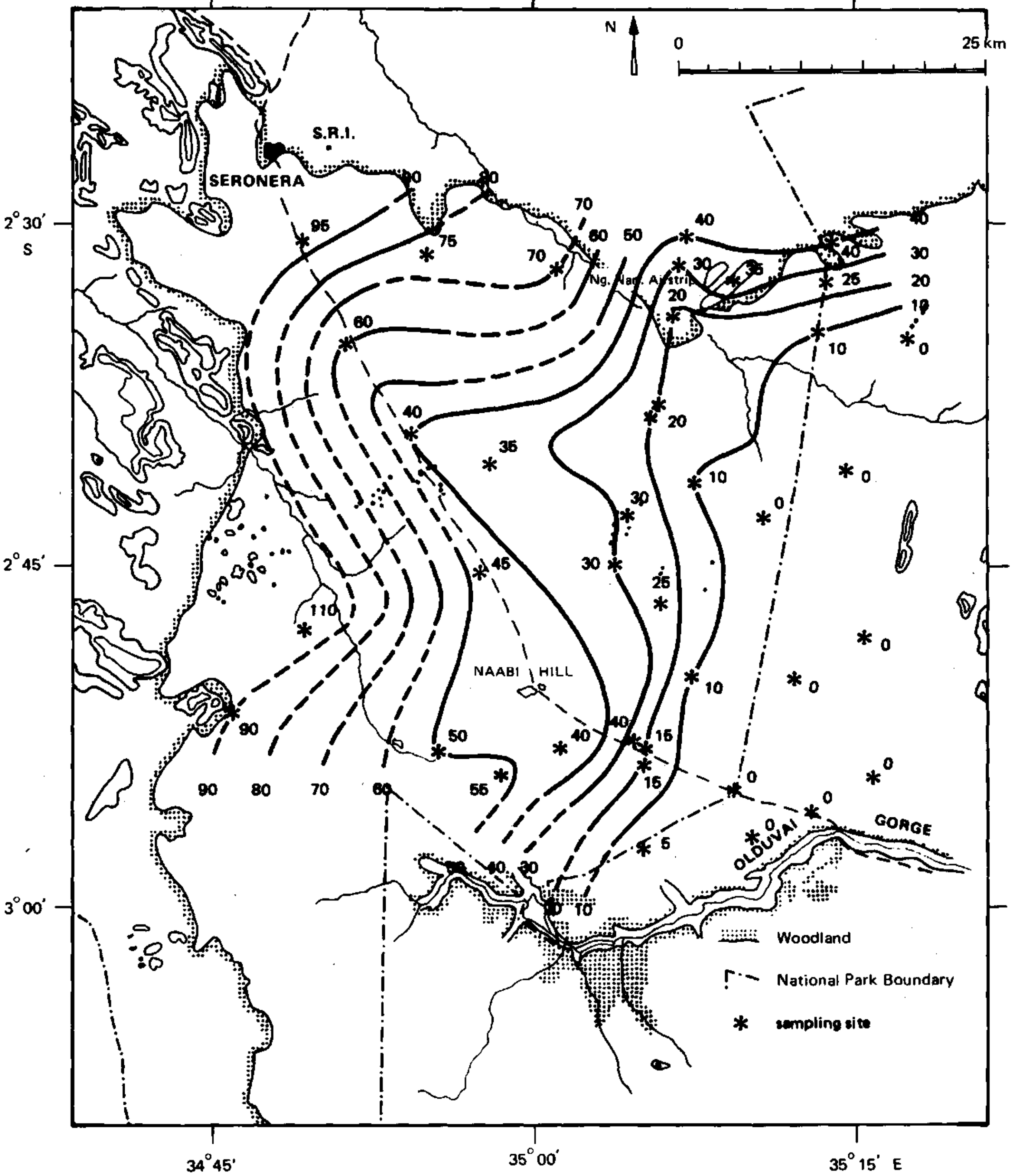
GV profiles) the ESP's from the experiments were higher than the ones calculated according to the above formula; at high concentrations of soluble Na (GS III), the experimental and the theoretical ESP values corresponded fairly well. The EPP values from the experiments were higher than the calculated percentages for most samples of the GV and GL II profiles; for the GS III profiles, however, the opposite was found. In the latter case the high amounts of soluble Na^+ - which ion has a strong ability to replace K - may have had a competitive (negative) effect on the K-adsorption. In the case of the GL II and GV profiles, in which soluble Na was of minor importance, the competition effect was probably small. The somewhat too high experimental EPP-values (in comparison with the estimated ones) might indicate that K^+ was preferentially adsorbed by the amorphous minerals (compare with Van Reeuwijk and De Villiers, 1968: "Potassium fixation by amorphous aluminosilica gels").
Considering the particular mineralogy of the soils just discussed, and in spite of the differences observed between the estimated and experimental ESP and EPP values, the regression formulas given in the Agricultural Handbook 60 - which have been derived from a limited number of soil samples collected in certain parts of the U.S.A. - still produce fairly accurate estimations of the ESP and EPP-values.

Considering the above relationships for soils in other parts of the Serengeti Plain (Short grasslands and *Andropogon greenwayi* grasslands), the differences between estimated and experimental values were more pronounced (Table 29).

In most top soils and in soils with low EC_e-values throughout the profile, the relative amounts of exchangeable Na and K, found from the experiments, both exceeded the ones calculated on the basis of the SAR and PAR (often over 100%). An exception formed the

20-30 and 40-50 cm samples from NaNo-A profile (Andropogon greenwayi spot!), in which case the experiments yielded values that were much lower than the predicted ones; it should be noticed that the top 50 cm of this profile had a relatively low base saturation. Generally spoken, one might conclude that there was a preferential adsorption of K and Na in the top soils of the "Short" and Andropogon greenwayi grasslands. In the strongly alkaline subsoils (BARSEK, NaNae 2; both profiles were located in the Short grasslands) the relative amounts of exchangeable K stayed far below the values estimated from the PAR (not in Table), probably as a result of the strong competitive effects caused by the high concentrations of soluble Na in these parts of the profiles. Also the relative amounts of exchangeable sodium were lower than the calculated values, but not to the extend that was found for potassium.
The laws of cation exchange - as expressed by the Handbook 60 regression formulas - seem therefore less applicable for the soils of the "Short" and Andropogon greenwayi grasslands. In view of the similarity in parent material and profile development this might also be the case for many of the loamy ridge top soils in the Long grasslands.

Fig. 35: Depth contours (cm) of lime contents ≥ 1 %



2.4. Miscellaneous Land types

The Miscellaneous Land types include soils that have formed under special topographic or hydrological conditions or that have developed from parent materials or rocks that are different from those in the direct surroundings and that occupy only small areas. Several of them have already been discussed or mentioned in the discussions of the three soil landscapes of the Serengeti Plain.

2.4.1. Sandy and loamy soils of deeply incised valleys and valley walls, shallow or very shallow, overlying basement rock or petrocalcic horizons (IV.1).

The soils have derived from volcanic ash and are chiefly found along the walls of the Olduvai Gorge, in the valleys of the Magungu River and its side arms, in some parts of the Mbalageti valley ("Hidden valley") and in two depression-like incisions which form part of the drainage line that lies just to the east of the Park boundary. Small pockets of soil alternate with exposed banks of petrocalcic horizons or with outcrops of Pre-Cambrian rock in many places (e.g. schists and gneisses in the Magungu valley).

In some places - namely in the northernmost one of the two depressions just mentioned - successions of petrocalcic horizons of different age show up clearly (aerial photograph!).

The Olduvai Gorge forms the most extensive unit within this landtype. It can be subdivided into two parts: the very deep canyon-like part east of the crossing with the Seronera-Arusha road - in this part the Beds I-VI of the Olduvai Sequence are found exposed - and the much shallower western part with gradually sloping walls in which the lakes Masek and Ndutu are found. In many places along the walls outcrops of petrocalcic horizons are found. Details about the geological history, the morphology and mineralogy of the lakebed deposits and the petrocalcic horizons that have formed in these layers have been described extensively by Hay (1976); some data can be found in Part I, Ch. 4: Geology.

The vegetation found on these soils is marked by grasses that are taller than those of the asjacent plain, by the presence of many herbs such as Indigofera basiflora, Justicia elliotii (Mbalageti valley), Hypoestes forskalei, and some single Acacia tortilis trees (valleys and depressions in the eastern part of the Serengeti Plain).

The vegetation in the Olduvai Gorge contrasts strikingly with all other vegetation types found in the study area: in many parts there is an overstory of Commiphora madagascariensis - Acacia tortilis - A. mellifera woodland of varying density; A. tortilis trees are more commun in the western, less steeply sloping parts of the gorge, A. mellifera predominates in the eastern part. In the lower story Sansevieria ehrenbergiana and Cissus sp. are the characteristic species. In fact, the Olduvai Gorge may have borrowed its name from the presence of the first species: the name Olduvai seems to be synonymus with the Masai word "Oldupai" i.e. Sansevieria. A more detailed description of the Gorge's vegetation has been given by Herlocker & Dirschl (1972).

2.4.2. Sandy, loamy and clayey soils of valley bottoms, riverbeds and small alluvial plains, deep, predominantly saline-alkaline (IV.2).

The soils of this landtype occupy only a small part of the study area. They differ from the other valley bottoms and riverbeds shown on the soil map in the following respects:

- strong variance in soil texture and soil structures over short distances; intricate complexes within a unit.
- parent material differs from that of the soils of the adjacent

soil units (flank, valleywalls) because of its alluvial origin; flattened or rounded gravel, derived from the Pre-Cambrian basement, occurs in many places.

- salinization, often indicated by salt crusts on the soil surface during the dry season, is found in various places. An example of a profile marked by external salinization is given in Appendix 8[1].

The alluvial soils support various vegetation types. Along the major river courses near the north-western edge of the plain high <u>Acacia xanthophloea</u> trees (also called yellow barked Acacia) form tree-lines which are a striking feature within the landscape: Seronera River and tributaries, the Mbalageti River, the Ngare Nanyuki River; the lower vegetation layer consists of bush (<u>Aspilia</u> sp.) and tall grasses - up to 1 metre high - like <u>Chloris gayana</u>, <u>Pennisetum mezianum</u> and, in the more saline/alkaline parts, also <u>Sporobolus consimilis</u>. Other stands of <u>A. xanthophloea</u> are found in the Olduvai Gorge and the Ngare Nanyuki "riverine forest".
In strongly salt-affected soils - e.g. in various places along the Seronera River, Mbalageti River, Magungu River and the Olduvai Gorge short grasses form the main component of the vegetation. Characteristic species are: <u>Sporobolus homblei</u>, <u>S. spicatus</u> and <u>Odyssea jaegeri</u>; at salt-encrusted spots the latter species was often dominant.

2.4.3. Complexes of sandy loamy and clayey soils of kopjes (Inselbergs) and kopje pediments, shallow to deep, derived from residual materials, strongly influenced by volcanic ash (IV.3).

<u>On the soil map</u> bare rocks, debris, loose boulders at the base of and between the large rocks and gently sloping kopje pediments have been collected under one unit: "kopje complex".

[1] available at the Dept. of Tropical Soil Science, Agricultural University, Wageningen, Holland.

"Kopje complexes" often occupy such small areas that it was not feasible to indicate these areas by colour; in such cases a symbol representing a single kopje was used in stead of using the appropriate colour for this unit.

The kopjes that are found scattered throughout the Serengeti Plain can be subdivided into 2 groups:

- predominantly granitic rock;
- predominantly gneissic rock; these kopjes belong to the "Serengeti Group" (Pickering, 1958)

Descriptions of the types of rock and mineralogical composition have been given by Pickering (1958, 1960) and Macfarlane (1967,1968). Gerresheim (1974) gives a detailed description of the Moru kopjes, which are situated near the western boundary of the Plain; this group stands out from others by its large number of kopjes and the enormous size of some of them. Within the landscape of the Moru kopjes Gerresheim distinguished 6 land facets on the basis of topography and drainage conditions, which could be subdivided into 10 so-called land elements.

The Simba kopjes, which are found further to the east, also consist of granitic rock; this group includes also a large number of kopjes, but the average size of the kopjes is much smaller than that of the Moru kopjes. Other groups of kopjes composed of granitic rock are the Soit O Gnum kopjes (south of Old. Olobaie), the Soit Ol Modison (Masai) kopjes (about 10 km south-east of Seronera) and the Olborturoto kopjes (about 10 km south-east of the SRI).

The kopjes in the eastern half of the study area are mostly composed of gneissic rock (Serengeti Group). The largest outcrop is Naabi Hill which rises high above the surrounding plain; its size exceeds that of the largest kopjes of the Moru Group.

Other groups are: the Gol kopjes, which are located in the central part of the Plain, scattered over a large area; for practical reasons some clusters belonging to this group, have been indicated by separate names: Zebra kopjes for the northern members, South-east kopjes for a cluster in the south-eastern part of the park, the Barafu and Soguna kopjes in the north-eastern part of the Plain. Some of the clusters, or some members of them, are located on ridges and form striking landmarks (Masai kopjes, Gol kopjes, South-east kopjes, Barafu kopjes and Soguna kopjes).

The vegetation on the kopjes differs strikingly from their surroundings: tall grasses, shrubs or trees are found on most of them. The particularity of the kopje habitat shows up, for instance, from the occurrence of typical Long grassland grass species (e.g.Aristida adoensis) on kopjes in the Short grasslands. In the eastern part of the Plain most common trees are Acacia tortilis and Commiphora sp., while also shrubs like Maerua triphylla occur. Towards the west, at increasing mean annual rainfall, broad leaved shrubs form the major component of the vegetation cover (e.g.Maerua triphylla, Hoslundia opposita, Grewia fallax, G.trichocarpa). Trees like Ficus glumosa and Euphorbia candelabrum are quite common in the Moru kopjes. Details about the botanical composition of kopje vegetation can be found in Hoeck (1975). Naabi Hill, which lies near the centre of the Plain, is covered by a dense vegetation, in which Acacia tortilis and Commiphora trothae form the overstory. The special nature of the kopje vegetation is very likely to be related with a more favourable moisture supply in comparison with the situation in the grasslands: during wet periods high amounts of rainwater will collect in deep cracks and deep soil pockets between rocks and boulders, which form a source of easily available water for plant growth.

Although most kopje soils will have been strongly influenced by volcanic ash, the physico-chemical properties of the soils will be different from those of typical ash-soils because of the much more intensive leaching by rainwater.

Kopje soils, namely the soils in cracks and between boulders, are generally non-saline and have a neutral to weakly acid reaction. Salinity/alkalinty effects, which occur widely in the soils of the surrounding grasslands, are therefore not found in these soils.

2.4.4 Loamy soils of quartz hills, very shallow or shallow, strongly influenced by volcanic ash, locally overlying a petrocalcic horizon (IV.4)

This unit is of much less importance than the kopje complexes. Most of the quartz hills are gently sloping and form a striking feature in the nearly flat landscape of the Serengeti Plain. The soil profiles on the hills are mostly shallow and will have physico-chemical properties comparable with those of the kopjes (non saline, non alkaline). The vegetation found on this unit, however, is less luxuriant than on the kopjes. A possible reason for this is the lacking of deep cracks or the absence of deep pockets of soil between rocks.

2.4.5 Soils of marshes, predominantly saline-alkaline (IV.5)

Marshes are found along river courses and drainage lines, e.g. in the Olduvai Gorge (western tributaries), along the Mbalageti River (north-east of the Moru kopjes), in some places along the Seronera River and the Ngare Nanyuki River, but also as slight depressions in higher elevated places like the flat area in the western part of the Andropogon greenwayi grasslands, which forms partly a part of the main watershed between the Lake Victoria and the Olduvai Gorge catchment areas. The soils are wet during most of the year (udic or aquic moisture regimes).
The vegetation is often marked by the presence of the tall, salt tolerant grass Sporobolus consimilis and Cyperaceae.

2.4.6 Soils of mud flats of shallow soda lakes, strongly saline-alkaline (IV.6).

They are found along Lake Ndutu (soda), Lake Masek, Lake Magadi (soda) and along two small soda lakes Ngorono and Kasciya. When the soils have fallen dry (during the dry season) they are covered by a salt crust, which consists for a great part of Sodium Carbonate and Bicarbonate. The soils are black, due to dispersed organic matter. The mudflats are bare. At lake Ndutu a Suaeda species is found on the more elevated parts.

2.4.7 Sandy (pseudosandy) soils of dunes (IV.7)

Most of the dunes are found in the A.1 area (south-eastern part of the Short grasslands). They occur -usually in groups- on upper flanks that are facing the west, on the western sides of flat valley bottoms and locally on ridge tops. In some places they form chains that follow the drainage lines e.g. north of the main road between the Park entrance and the Olduvai crossing (see map). The area, in which the dunes are found, extends south by the Gol Mountains towards the Salei Plain in the east. Individually the dunes have a longitudinal shape and have an east-west orientation, in correspondance with the prevailing easterly winds from the Crater Highlands passing south of the Gol Mountains. Locally their shape tends towards a barchane. True barchanes occurred in the area between the southernmost range of the Gol Mountains (Olongoidjo) and the Olduvai Gorge; aerial photographs show that these dunes had travelled over considerable distances ("trails" could be followed over a distance of 7-10 km.). The barchanes seem not to have stabilized yet ("shifting sands"). The heights of the longitudinal dunes vary between a few decimetres to several metres. Dune deposits of considerable thickness are found on the ridge just south-west of the former Ngorongoro Conservation Unit entrance gate, 2.5 km south-east of the entrance of the Serengeti National Park. Along blown-out parts stratification of the parent material was well visible.

The dark grayish material had sandy or fine sandy textures; apart from the high percentage of very dark coloured heavy minerals, the sand fraction probably consisted of very fine aggregates of amorphous minerals and heavy minerals cemented by lime (pseudosand); the organis matter contents were low (less than 1%, see Anderson & Talbot, 1965). The unexpectedly high CEC values have been discussed in Chapter 2.1.

In most places the dunes cover very fine sandy or loamy volcanic ash soils (old surfaces, buried profiles), that have a petrocalcic horizon at some depth; in former eroded areas the dunes are found immediately on top of the petrocalcic horizon.

2.5. Decalcification of the soils across the Serengeti Plain, as related to the mean annual rainfall pattern.

Fig. 35 shows depth contours at 10 cm intervals of lime contents $\geqslant$ 1%; Fig. 6 the mean annual rainfall pattern for the years 1968-1973. The 1% limit was chosen because it represents the lowest content at which a reaction of lime with hydrochloric acid is audible. The contours have been constructed by linear interpolation from data obtained from soil profiles situated on ridge tops and in level areas. This was done in the first place because in the latter soil units leaching and accumulation processes are chiefly governed by vertical movements of the soil moisture (rainfall and evaporation) and secondly because soils of the ridges and level areas showed greatest similarity in soil texture and profile development, porosity and infiltration characteristics, while these soils were also assumed to be - more of less - equally affected by erosion processes. Comparison of the patterns shown in the figures 35 and 6 reveals some interesting points of correspondance but also some differences. As it could be expected, there was a positive correlation between the depth of decalcification and the mean annual rainfall. The following coinciding trends should be noticed:

- A weak gradient - roughly east-west - in both decalcification depth and mean annual rainfall across the central-northern part of the Serengeti Plain.
- Steep gradients in decalcification and mean annual rainfall in the area between Naabi Hill and the south-eastern Park boundary and in the north-western part of the Plain.

The differences between decalcification and rainfall distribution are the following:

- The area between Naabi Hill and the western boundary of the

Serengeti Plain (Uplands) - also known as Andropogon greenwayi grasslands - is marked by a weak rainfall gradient; the gradient in decalcification, however, seems - in spite of the lacking of a sufficient number of data for this area - fairly steep, although the shapes of the contourlines - e.g. the 40 and 90 cm lines - and of the isohyets (650 and 750 mm) look rather similar. It should be remarked, however, that the rainfall distribution pattern had been based on data collected only during 5 years; the actual annual distribution of rainfall might be different from the situation shown on the map.

- A very interesting situation is found along the northern boundary - between the grassland Plain and the woodlands - between the Ngare Nanyuki airstrip and Soit Ayai Park Entrance (eastern Park boundary): wehereas the rainfall gradient is weak (east-west), there is a marked increase of decalcification with a gradient running almost into a south-north direction. For the same area the rainfall distribution maps given by Norton-Griffiths et al. (1975) show a clear deviation of the 600 mm isohyet towards the east.

A steep rainfall gradient in het area between Ngare Nanyuki and Soit Ayai Park Entrance, at right angles with the grassland-woodland boundary, would correspond well with situations in other parts of the grassland-woodland boundaries (north and north-west) and would also support the widespread opinion that woodland in the Serengeti region only occurs if the mean annual rainfall exceeds a certain number of mm (c.q. 600 mm). Again it should be mentioned that the mean values of 5 years rainfall data might not represent the actual situation; the presence of a rainfall station north of the Soit Ayai Park Entrance would have contributed considerably in obtaining a better picture.

In case the isohyets as drawn in Fig. 6 would represent the actual rainfall distribution in the area concerned there should be another explanation of the rapid increase of the depths of decalcification, while also the possible relationship between the occurrence of woodland and available moisture would become less relevant.
The steep gradient of decalcification in the north-east might be explained by the assumption that the area just south of the woodland-grassland boundary has become rejuvenated by recent ash deposits (calcareous!); unless the ashes have been deposited very locally, this hypothesis would be contradictory to the similarities between rainfall and decalcification pattern described before.
Reliable evidence for local rejuvenation could not be established: detailed mineralogical analysis (heavy minerals) of the sand fraction of samples from different areas will be needed for a definite answer to this point.

3. Special features.

3.1. "Step erosion".

Little is known about the origin and occurrence of this phenomenon, which occurs abundantly in the A.4 area (soil landscape I.1: Short grasslands). A short description of it has already been given in 2.1.4. Several investigators did some work on the occurrence of erosion steps. Anderson and Talbot (1965) suggested that the origin of the erosion steps was due to the high instability of the "calcimorphic" soils, caused by high silt and sand contents and high percentages of exchangeable sodium; they were said to be especially common on slopes of over 5%, which suggests that also slope gradient contributed to the formation of the steps.

Glover and Wateridge (1968), who studied "erosion terraces" in the Loita Plain (west of Narok, Kenya), found that the terraces were maintained by a regressive erosion (crumbling away of soil material) of about 2,50 metres per year; the erosion was caused mainly by trampling of Masai cattle and game animals, while also digging activities at the erosion faces were recorded in places where the subsoil was saline. No clear effect of the rainfall could be established, although damage on the terraces caused by trampling under wet conditions was mentioned as serious. For the formation of the terraces 3 factors were thought to be relevant: trampling, alternating horizontal soil layers of different hardness and wash by rainwater (mainly as a result of trampling). The authors also referred to the terrace erosion in the Serengeti National Park, for which the wild animals were thought to be responsible instead of cattle. Some comments on this follow later.

Anderson and Herlocker (1973) mentioned the occurrence of erosion steps on "dry saline/alkali soils" (internal solonchaks) on the floor of the Ngorongoro Crater; the soils and the grassland types strongly resemble those in the eastern Serengeti Plain (soil landscape I.1). They ascribe the step formation to a physical instability due to high silt and sand contents in combination with high amounts of exchangeable sodium, which were thought to disperse fine particles and to hinder the formation of stable aggregates. The step erosion was aggrevated by animal activities like licking and scraping the soil (for salts?). Finally also run-off on 3-4^{o} slopes may cause gullying and start step-development To explain step formation and the maintenance of the steps, Anderson and Talbot (1965) and Anderson and Herlocker (1973) referred to the physical-chemical instability of the soil with additional effects of game animals and run-off, while Glover and Wateridge (1968) stressed the effects of trampling (mechanical instability).

Personal observations and investigations may give a somewhat different view on the occurrence and origin of this phenomenon:

Soil pits, that had been dug in the Short grasslands (and also on ridges of the Andropogon greenwayi and the Long Grasslands!) and that had remained open for over 1-2 years, appeared to remain intact. During this period the walls of the pits had hardly suffered from crumbling away; slight damage had occurred in the top layer (0-20 cm) only.

The same can be remarked for a number of erosion scarps and steps, that were observed regularly by the present author during 3 consecutive years. Regressive erosion could not be established. Soil pits that were dug in alkali-soils (e.g.at the "short grass"spots in the Long grasslands),on the contrary, were found to collapse completely when exposed to wettness (wet season). As soil material from the natric horizon had formed an impermeable layer on the bottom of the pit, the pit became soon a pool, which resulted,in its turn,in a further collapsing of the walls of the pit. In spite of the higher salt and sand contents of the soils that belong to the first category (Short grassland soils etc.) -they still had clay percentages of over 30%- and in spite of the high amounts of exchangeable sodium on the exchange complex in the strongly saline/alkaline subsoil (usually below 30-40 cm), detoriation of the subsoil structure (spongy porosity!) as a result of dispersal of the finest fraction, did apparently not occur in these soils. The stability of the spongy structure was also shown during infiltration experiments: infiltration rates remained perfectly constant during the time the experiments were carried out. The soil probably owes its stability to the cementation (weak) of the mineral fraction by lime, which is found in substantial amounts in the soils marked by step erosion. The finer textured surface soil, in which the lime contents were generally low, tended to be less stable although the amounts of exchangeable calcium on the adsorption complex were usually high. The fact that the erosion steps and scarps may owe their shape to the high stability of the (saline-)alkaline subsoil seems somewhat paradoxical. This theory contrasts strongly withthe one of Anderson and Herlocker mentioned before. Stress -e.g.trampling, digging, car driving- exerted upon the soil material under wet conditions, however, strongly affects the structure of the soils, due to the thixotropic properties of the soil meterial (see Ch.2.1.2: physical characteristics). For the soils in the erosion step area (A.4 area) trampling by game animals, as suggested by Glover and Wateridge, would be a destructive factor rather than one which would contribute to the forming and maintenance of the steps or scarps. Other arguments against the trampling theory are:

- Before the Serengeti Plain -as far as the study area is concerned- became part of the National Park, it was used by the Masai for extensive cattle ranching; at that time the erosion steps were already present (1953-1958 aerial photographs). The number of game animals was fairly low in comparison with the present situation.
- From the moment the Masai had left the area, the total number of migratory animals has increased tremendously: about a factor of 10 times, up to a number of over 2,000,000 (see Part I. Ch.1: Introduction). On the basis of a comparison of 1972 aerial photographs with those of 1953-1958, the number and positions of the erosion steps seem not to

have undergone a significant change.

- Erosion phenomena, that had definitely been caused by cattle and game animals, namely the tracks that run towards waterholes, had not spread any further from the time the area forms part of the Park; locally, tracks and eroded areas have even been recovered by the vegetation.

As far as the slope gradient is concerned, it should be remarked that on slopes in the south-eastern part of the study area (A.1, A.2 areas) that have slope gradients equal to those in the step erosion area (A.4) no well developed erosion steps are found, in spite of the fact that the grass cover is lower (A.1 area!) and that considerable surface erosion has taken place (hummocky relief!). The latter type of erosion was probably caused by overgrazing. Nevertheless, these soils -which are calcareous up to the surface, see Ch.I.2.1, I.2.2 - seem stable enough to escape the forming of steps. Towards the north-west, at increasing decalcification (see Ch.2.5: Decalcification, fig.35) the steps become more frequent and also higher. The most strongly developed steps are found in the A.4 area. Near the boundaries to the Long grasslands and Woodlands -the soils now have a thick non-calcareous top layer- the steps are lower again. It seems therefore, that the occurrence and heights of steps and scarps are primarily related with the thickness of the decalcified top soil. The slightly less stable, decalcified, top soil appears to allow the forming of steps. Besides the regional differences in step development, there were also catenary differences: lower steps on the upper flanks, higher steps halfway the slope and low steps on the lower flanks (personal observations). In the latter case the correlation between height of the steps and decalcification was found again. The weak development or absence of the steps in soils that have a thick non-calcareous top layer could be due to a too low stability of the sub soil: collapsing of the steps when a certain height is reached.

Summarizing one may conclude that calcareous soils are too stable to allow the forming of steps and non-calcareous soils too unstable to prevent the formation of erosion steps.

3.2: The occurrence and possible origin of spot-wise salinization in certain parts of the Andropogon greenwayi grasslands (soil landscape I.2)

To obtain a more accurate picture of the variations in subsoil salinity and alkalinity over short distances, two transects - NaNo I-V and NaNo VI-IX - were sampled in detail. Both transects were located on a ridge top about 10 km north-west of Naabi Hill, not far from the NaNo-A and B sites.
The transects were chosen across patches of Andropogon greenwayi grassland (almost pure stands, complete cover) and adjacent spots marked by a much more open grass cover (up to 40 per cent cover).
From soil/vegetation studies in the Long grasslands (soil landscape I.3) and the woodlands around Seronera (soil landscape II.2), termite activity was found to have strong effects on soil properties, viz. on the factors salinity, alkalinity and soil structure; the nature of the processes involved, however, had not yet been clearly understood.
The presence of termites at the NaNo-site had been overlooked for quite some time since the fairly high and bare termite mounds[1]), which formed a striking aspect within the landscapes of the Long grasslands and the woodlands, were lacking in this area. Attention to the presence of termites at NaNo was drawn by an aardwolf (Proteles cristatus) marking its territory. In the Serengeti this highly specialized predator was found to feed almost entirely

[1]) probably of Macrotermes subhyalinus (Kreulen, pers.comm.)

on one single species of termites: <u>Trinervitermes bettonianus</u>, a nasute, harvesting species, that builds small and low mounds (Kruuk and Sands, 1971). The presence of the aardwolf near the NaNo-sites may be indicative for the occurrence of <u>Trinervitermes bettonianus</u>; however, it is uncertain whether the mounds, that formed part of the transects chosen, were built by this species indeed.

The dimensions of the termite mounds varied considerably due to differences of age: recent mounds had diameters of 2 - 3 metres and heights of 20 - 30 cm at most, while older ones had become more or less strongly levelled with diameters over 3 metres and heights of 10 cm or less; many of the mounds were rather inconspicuous because they were overgrown by grasses.

The termite mound vegetation generally resembled the more open grassland type, in which <u>Digitaria macroblephara</u> and <u>Pennisetum stramineum</u> were the dominant species: <u>Andropogon greenwayi</u> was mostly absent except on the most recent mounds.

The NaNo I - NaNo V transect, outlined in Fig. 36, represented a situation across a fairly old - but still active - , levelled mound and an adjacent <u>Andropogon greenwayi</u> spot.

The NaNo VI - NaNo IX transect, outlined in Fig. 37, included a recent termite mound surrounded by <u>Andropogon greenwayi</u> grass cover. Analysis results of both transects have been given in Appendix 43.

In the figures isolines of various levels of salinity (expressed by EC_e-values) and alkalinity (expressed by pH-values) have been outlined. The isolines have been constructed by interpolation and extrapolation of EC_e and pH-values; as a simplification the assumption was made that gradients of salinity and alkalinity throughout the soil were linear.

In the cross-section through the recent termite mound (NaNo VI - IX), the highest salinity was found near the centre of the mound: moderately

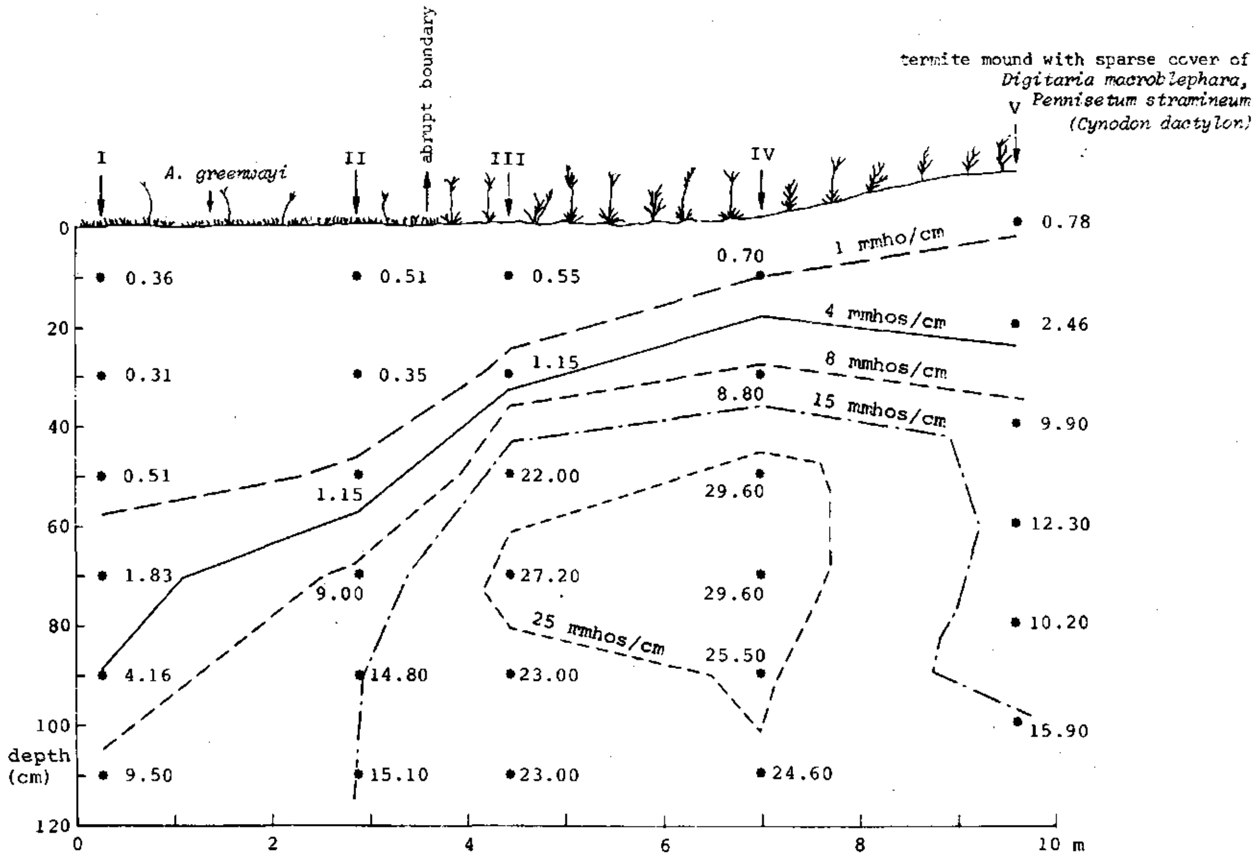


Fig.36a: NaNo I-V: Transect through *Andropogon greenwayi* spot and old termite old termite mound; salinity pattern (EC_e in mmhos/cm at 25 ^oC).

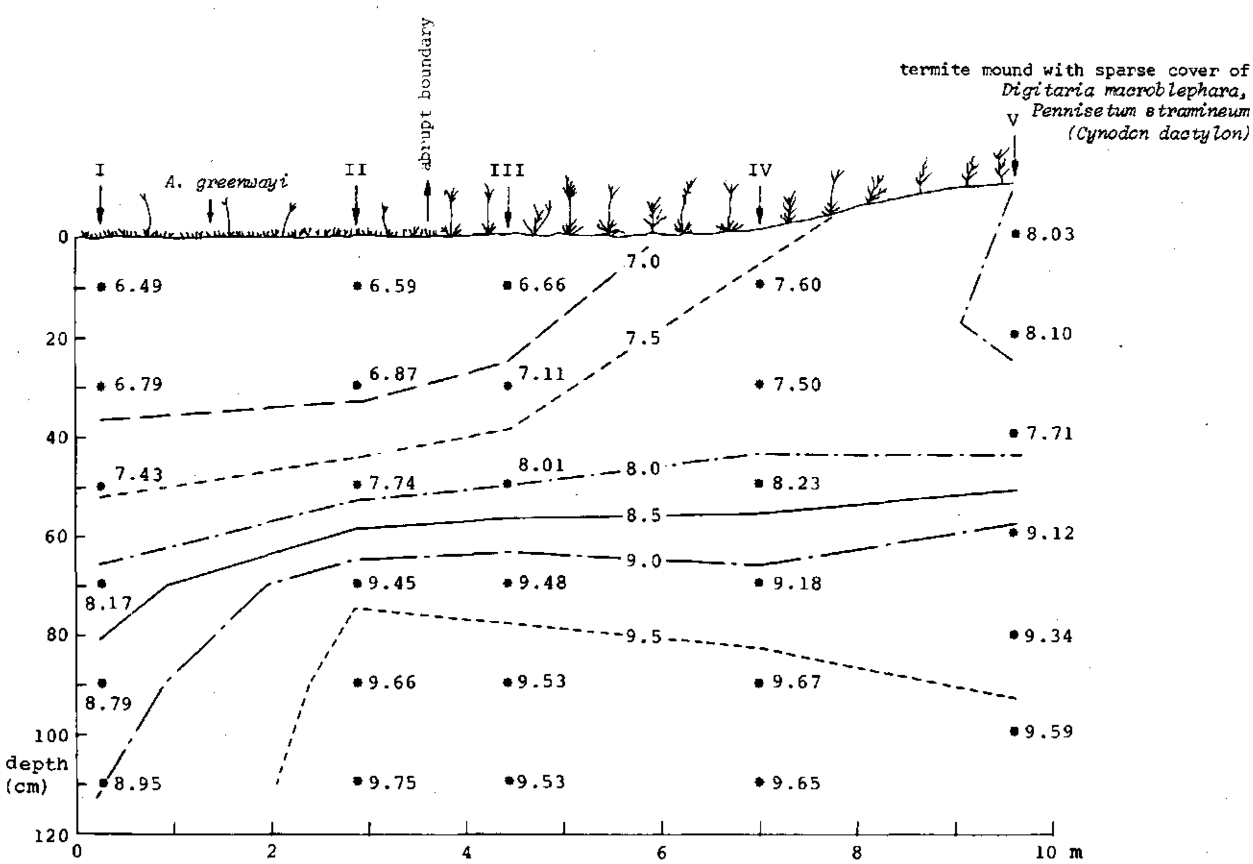


Fig.36b: NaNo I-V: Transect through *Andropogon greenwayi* spot and old termite mound; alkalinity pattern (pH-values of saturated pastes).

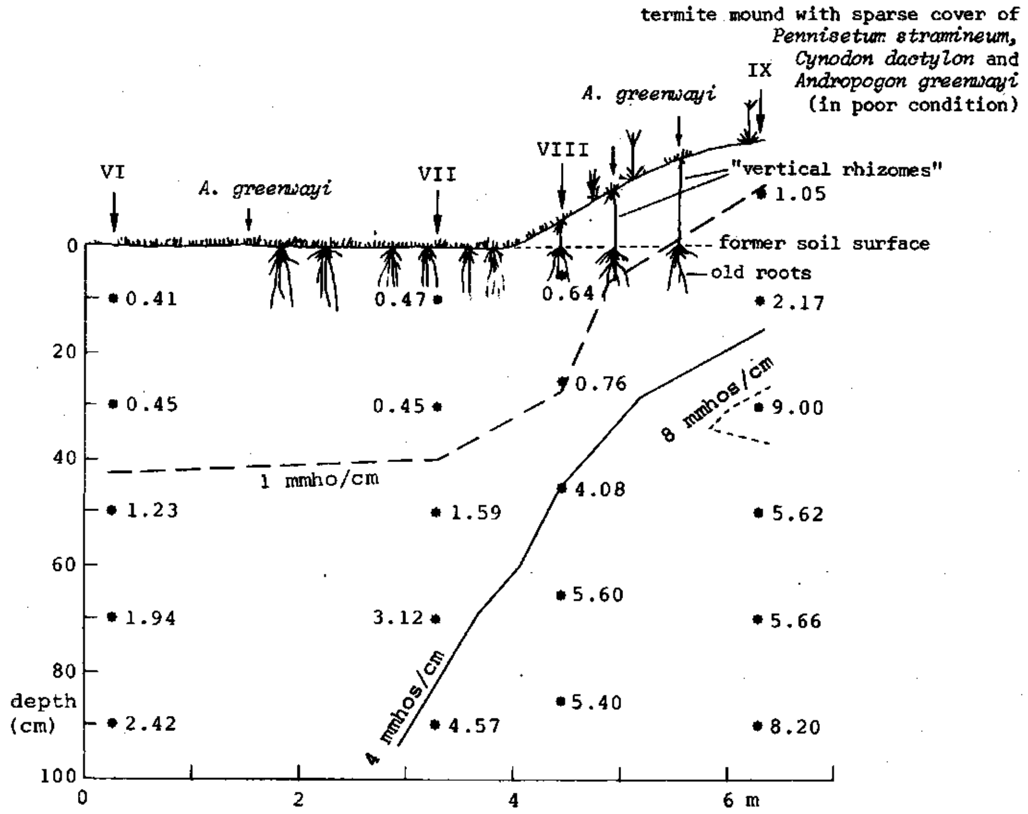


Fig.37a:NaNo VI-IX: transect through *Andropogon greenwayi* spot and recent termite mound; salinity pattern (EC_e in mmhos/cm at 25°C).

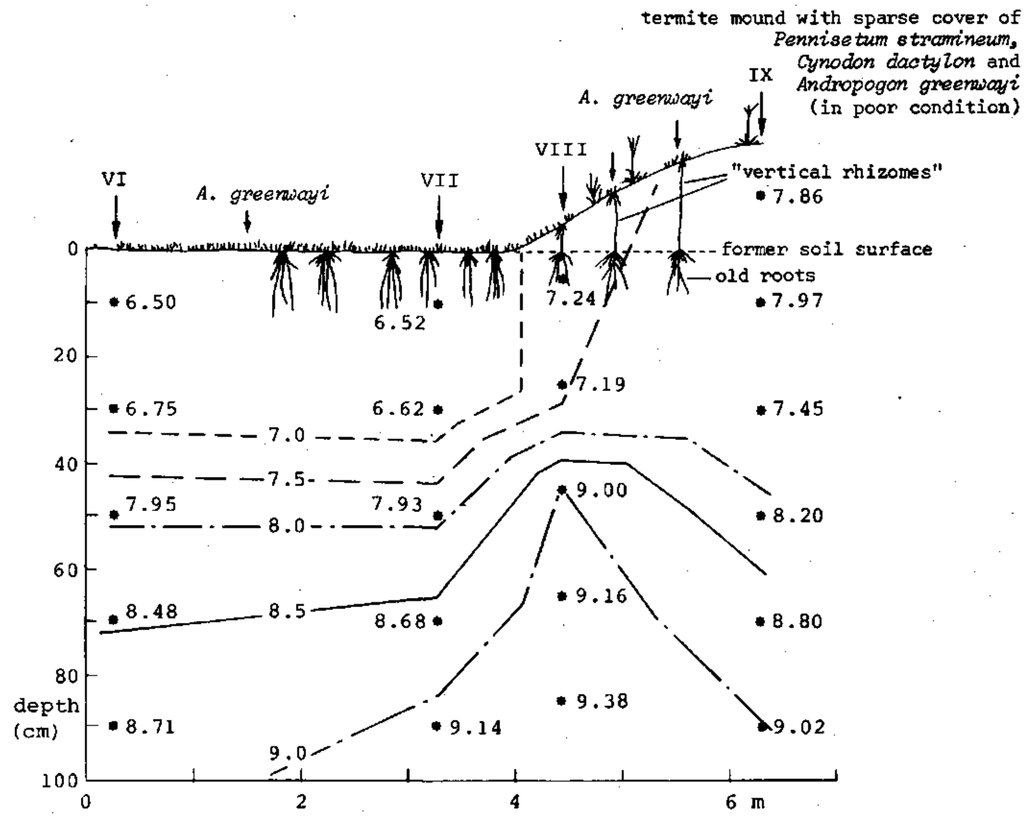


Fig.37b:NaNo VI-IX: transect through *Andropogon greenwayi* spot and recent termite mound; alkalinity pattern (pH-values of saturated pastes).

saline at 50 cm depth; the 4 mmho-isoline went steeply down just below the base of the termite mound. Profile VI, which was located in the centre of the Andropogon greenwayi spot, was at least salt-free in the upper 100 cm. In profile VIII (boundary between Andropogon greenwayi and the termite mound vegetation) there was a rather abrupt increase of salinity at a depth of appr. 40 cm. The isolines of alkalinity showed a rather similar pattern, except for the upward alkalinity peak in profile VIII at a depth of about 50 cm, which was indicative for a relatively high amount of bicarbonates and carbonates. Under the Andropogon greenwayi grassland (profiles VII and VII) the pH increased gradually with depth, reaching the level of strongly alkaline below 70 cm.

The salt composition in profile IX was marked by an unusual high amount of free nitrate (over 80 meq/l at 40-60 cm depth!); at depths between 60 and 80 cm nitrate amounted over 90% of the sum of ions. Sodium was the dominant cation, potassium amounted roughly 10% of the total cations, whereas calcium plus magnesium were exceptionally high in the 40-60 cm layer (low pH, high conductivity!). The data from profile VI formed a striking contrast: only in the deepest layer there was a trace of free nitrate; Na became dominant at EC_e-values over 1.00 mmho/cm, the relative amounts of potassium increased strongly towards the surface, and the amounts of Ca+Mg were normal (compared with situations elsewhere in the Andropogon greenwayi grassland).

Checks for free nitrate made on samples from profiles VIII and VII were clearly positive in profile VIII below a depth of 40 cm, while in profile VII only a trace was found below 80 cm.

The cross-section through the older mound and the adjacent Andropogon greenwayi spot (NaN_o I - NaNo V) shows important differences in salinity and alkalinity patterns in comparison with the first transect. The salinity in the central profile (V) exceeded the salinity in the fresh mound (IX) at lower depth only. A much stronger degree of salinization, however, was found several metres from the centre in the profiles III-IV: the 4 mmho-isoline occurred between 20 and 40 cm from the soil surface and a zone of strong accumulation of salts had formed below 60 cm depth.

In profile II (Andropogon greenwayi spot), the isoline of 15 mmhos/cm steeply down; the depths, at which the 8, 4 and 1 mmhos/cm isolines were found increased more gradually towards the centre of the Andropogon greenwayi spot. It should be noticed that the Andropogon greenwayi spot was comparitively small and that salinity occurred already within 60-90 cm.

The alkalinity patterns showed similar tendencies. Starting from the situation in the termite mound profile (V), the zone, in which the soils were strongly and very strongly alkaline (pH $>$ 8.5 - 9), was found to extend as far as profile II (inside the Andropogon greenwayi spot!); in fact, the highest pH-values recorded throughout the transect, were found in profile II. Highest pH-values did not coincide with highest salt contents.

The composition of the soluble salts and the changes in composition from the centre of the mound towards profile I shows a great similarity with the situation in transect VI-IX: the decrease of the relative amounts of sodium, especially in the top 40-60 cm, the increase of the relative amounts of potassium and again the very high amounts of Ca+Mg in profile IV between 20 and 60 cm (high EC_e, relatively low pH!) versus the fairly low ("normal") contents throughout profile I. This similarity showed up even better in the nitrate contents: the amounts of nitrate found decreased gradually towards the centre of the Andropogon greenwayi spot, whereas the depth, at which free

nitrate was detected, increased in the same direction.
The advanced stage of salt accumulation in the old mound (NaNo I-V transect) should be considered as a result of pedological processes; the initial stage as found in the fresh mound (NaNo VI-IX) may be largely due to termite activity, i.e. biological processes.
Data in the litterature on termite activity in soils seem to agree with the data found at the NaNo-sites: most workers found an increase of the pH, CEC and base saturation relative to the surrounding surface soil, in some cases accompanied by an accumulation of secondary lime. There were, however, different opinions on the processes leading to the accumulation of bases. Boyer (1956) found in mounds of Bellicositermes natalensis that the contents of CaO, MgO, K_2O and Na_2O in the nests and fungus combs were 10-20 times higher than in the surrounding soils. Especially high amount of CaO were found in the fungus combs: up to 3.5% (Joachim and Kandiah, 1940).[1] Hesse (1957) concluded that the relatively high amounts of calcium found in the fungus combs could not explain the higher CaO content for the entire mound. In a study on termite mounds (Macrotermes spp.) in Kenya and Tanzania, Hesse (1955) attributed accumulation of calcium carbonate in termite mounds to evaporation of calcium charged groundwater from the mounds surface, which process might have been favoured by transpiration of the vegetation on the mounds. The calcium carbonate was even found to form concretional layers at the base of the mounds. Hesse also found that the lime content increased with the age of the mounds; it was remarkable that the lime accumulation seemed to be restricted to uninhabited mounds, except in case the mound was built from calcareous soil. These facts indicate that the process of accumulation described by Hesse was pedogenetic.
Watson (1962, 1969), who studied the movement of soil moisture in

termite mounds[1]) in Rhodesia, estimated that the age of termite mounds should be several thousands of years to explain the base enrichment as a result of groundwater flow; as a maximum age for the mounds he mentioned 700 years, i.e. too short to explain the accumulation process according to Hesse (1955). The concentrations of various ions in the groundwater, however, were very low! (Ca+Mg: 0.08 meq/l!).

Other workers viz. Milne (1936[2]) in Tanganyika, Griffith (1938[2]) in Uganda found lime accumulations in termite mounds in a non-calcareous environment.

It seems, therefore, that Hesse has underestimated the role of the termites (active mounds) in accumulating bases for nests and fungus-combs, especially in view of the fact that termites continuously eat the combs and their dead, thus releasing the mineral elements by their excrements and saliva.

A major difficulty in the discussion on this subject is formed by the fact that many of the studies were carried out on different termite species and in areas that had totally different soils and climatic conditions. Therefore, the separate effects of the base enrichment in the fungus combs and the enrichment by capillary rise of groundwater followed by evaporation will have different weights in the accumulation process and will depend on climate, nature of the soil material and chemical composition of the salts in the groundwater.

How does the above apply to the NaNo-data?

The effects of the pedological process are clearly visible in the transect through the old mound (NaNo I-V transect, advanced stage

[1]) inhabited mounds of Odontotermes badius,
uninhabited mounds of Macrotermes bellicosus.

[2]) in Lee and Wood (1971)

of salinization). The accumulation of salts at some depth near the fringe of the mound was caused by the combined effects of mean annual rainfall, evaporation, run-off and subsurface transport of soil moisture and salts from the mound towards its surroundings. (N.B. due to the high pH in this zone all calcium and magnesium ions coming from the mound will precipitate as carbonates!).
With this, the accumulation of salts in the recent mound (NaNo IX) is still unexplained, and Hesse's theory of evaporating groundwater seems to be irrelevant merely because a groundwater table - even a temporary one during the wet season - was absent, mainly as a result of the favourable drainage conditions.
Also transpiration effects on the upward flow of moisture, are estimated to be small since the vegetation cover on the mounds was very sparse; moreover, the grasses will wither soon after the rains have stopped. N.B. The possibility of an upward flow as a result of special constructions or adaptations by the termites - in order to regulate the moisture regime in the mound - has not been taken into considerations; it should not be overlooked.
Therefore, it seems plausible that termites played an active role in the initial stage of accumulation:

1. using easy weatherable subsoil material of higher salinity and alkalinity for building the mound; this would compensate for the accumulative effects caused by capillary rise of groundwater, mentioned by Hesse (1955)
2. enrichment effects by the breakdown of fungus combs, dead termites, dung and other organic material.

The special composition of the salts found in profile NaNo IX may support the hypothesis of enrichment by the breakdown of fungus combs etc.:

- the relatively very high amounts of free nitrate; Kozlova (1951) also found large accumulations of nitrate in termitaria of Anacanthotermes ahngerianus in Central Asia (0.85% nitrate in the mound versus 0.022% in the surrounding soils); the mound material was used by farmers as a fertilizer; Kozlova attributed the high nitrate contents to a favoured mineralization of organic nitrogen compounds (N.B. termites have a protein content of 36%!) due to favourable temperature and moisture conditions.
- relatively high amounts of calcium and magnesium between 20 and 60 cm, which may have been derived from decomposed excrements and fungus combs.

Salt accumulation of concentrations comparable to those in the NaNo IX (and also NaNo V) profiles were also recorded by Ghilarov (1962)[1] water soluble salts 1.3% in the termitaria versus 0.06% in the surrounding soil; dominant anions were chlorides and sulphates and by Watson (1962) who also found a considerable amount of free nitrate.

Watson (1962) gave the results (in water soluble salts) taken from an old, uninhabited mound. In his first sample (7), see Fig.38 calcium and magnesium were the dominant cations and nitrate and bicarbonate the dominant anions; no carbonate ions were found (relatively low pH!). In the other sample (14) sodium and potassium were dominant, accompanied by mainly bicarbonate and chloride, while also carbonate ions were found (relatively high pH).

The findings by Watson show the same tendencies as the data obtained from the NaNo-mounds; strongest similarity was found in the fairly old mound (NaNo IV, V).

Watson (1967)[1] found that mineral N-contents in Macrotermes goliath and Odontotermes latericius mounds were higher than in the surrounding soils. Laperre (1971), working in Mozambique, found amounts of available N in Macrotermes bellicosus mounds to be 5-10 times higher than in the surrounding soil, which was thought to be largely due to the presence of fungus combs.

Although the above facts agree with the hypothesis of nitrate enrichment by mineralisation of fungus combs, excreta, etc., some other possibilities should not be overlooked:

1. Enrichment from the more saline subsoil material. In many soils within the Andropogon greenwayi grasslands, the Short grasslands, and, also in the Long grasslands and woodlands, free nitrate was found in the upper 120 cm at varying depths. The concentrations in the soil moisture, however, were usually low and amounted only occasionally up to 50% of the total sum of free salts in non-saline and weakly alkaline soils. The occurrence of free nitrate in volcanic soils is not uncommon, but the amounts found in Serengeti Plain soils, in which no termite activity has been recorded, seem too low to account for the nitrate contents as found, for instance, in profile NaNo IX of the "fresh mound" transect.
2. Wild animals, chiefly ungulates, urinating on the mounds to mark their territories. The ureum would partially penetrate into the mound by the tunnels and might be converted into nitrate by nitrificating bacteria. This process might account for the presence of nitrate ions but these and other anions should be accompanied by relatively very high amounts of potassium; potassium was found to be by far the dominant cation in urine of a tame wildebeest kept at Seronera (Kreulen, personal commu-

[1]) in Miedema (1971)

nication). Since no particularly high concentrations of potassium were found, urine probably played only a minor role as a source of free nitrate in the termite mounds and surrounding soils.

It is unfortunate that the species of termites which had built the mounds, that form part of the NaNo-transects, could not be established. The description of the mounds as given by Kruuk and Sands (1971) and their findings about the selectivity of the diet of the Aardwolf for the termite species Trinervitermes bettonianus may point to the occurrence of the latter species. Since Trinervitermes bettonianus is a harvesting species and not a fungus grower, the supposed effects on the observed enrichment of bases and free nitrate by the mineralisation of fungus combs have to be left out of consideration.

The effects of the subsoil material used for building the mound and the decomposition of organic matter and excreta, on the other hand, would gain importance.

Another possibility might be that mounds of other termite species occur within the same area, namely Odontotermes badius, a fungus grower, very common in the Serengeti Plain, which also builts low mounds and of which remains have been collected from aardwolf faeces (Kruuk and Sands, 1971); in this case the NaNo-transects might still include mounds with fungus combs.

Information on the chemical status of the soils affected by termite activity and on the changes in the chemical status during the time could also be obtained from the botanical composition of the grassland mosaics and the vigour of the individual species. On the recent mound, between profiles NaNo VIII and IX, Andropogon greenwayi was marked by a stunted growth, forming sparse clumps;

below the level of profile VIII, Andropogon greenwayi covered the soil for nearly 100% and was in a much better condition. The small Andropogon greenwayi clumps on the mound had sprouted from vertical rhizome-like structures ("vertical rhizomes"), which had grown from an old grass clump at lower depth; both the clump on the surface and the "subterranean" one - the latter was in a state of decomposition - had a root system. The lengths of the vertical rhizomes corresponded very well with the level on which the Andropogon greenwayi clumps occurred on the mound, above the surrounding soil (see also Fig.37 NaNo VI-IX transect). These facts demonstrate that Andropogon greenwayi was present before the mound was built - i.e. the mound originated inside an Andropogon greenwayi spot - and that a number of specimens had formed vertical rhizomes to keep pace with the formation of the mound; the latter process may have taken place within one or a few years only. The sparse cover and poor conditions of the grass on the mounds, and the state of decomposition of the subterranean clumps, showed that Andropogon greenwayi was disappearing from the internally salt-affected ($NaNO_3$!) mound (profile IX). This was in agreement with the fact that Andropogon greenwayi occurred - without exception - on soils that were salt-free and that had a pH (paste) of less than 8.5-9.0 to depths of at least 60-80 cm.

In the direct surroundings both mounds, that were still covered for the greater part by Andropogon greenwayi, as well as mounds that were largely bare, were recorded; on the latter Andropogon greenwayi was found replaced by salt and alkali-tolerant grass species like Pennisetum stramineum , Cynodon dactylon or Digitaria macroblephara.

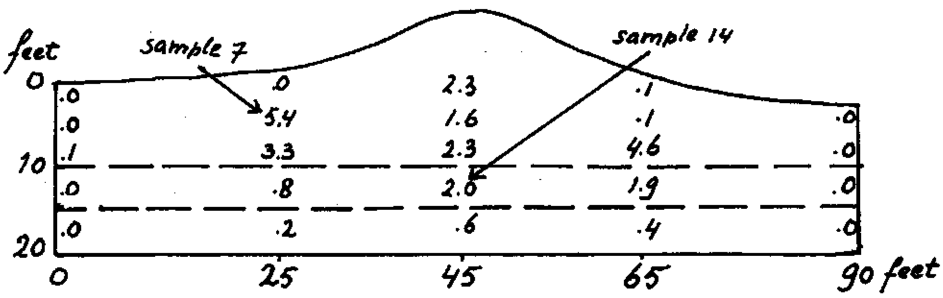


Fig.38a: The distribution of carbonates (expressed as $CaCO_3$ per cent, of fine earth) below a termite mound. (After Watson, 1962; derived from Miedema, 1971)

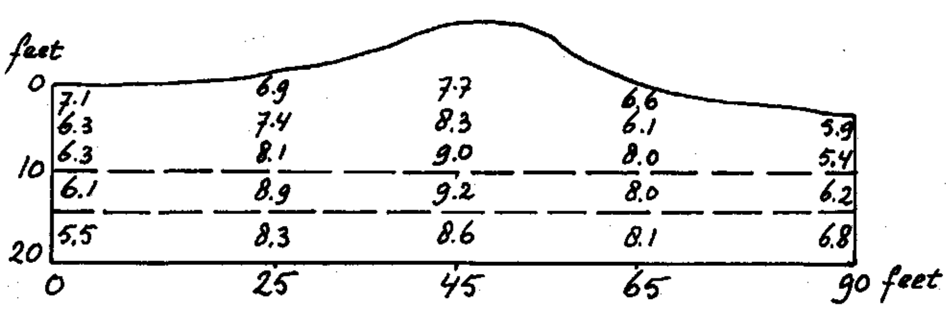


Fig.38b: The distribution of pH-values below a termite mound. (After Watson, 1962; derived from Miedema, 1971)

On the basis of the data collected from the NaNo-transects,the life cycle of the termite mounds and their effects on the chemical situation in the surrounding soils can be summarized as follows:
The termite mounds originate in the Andropogon greenwayi spots. During the active stage in the life cycle of the termite mounds, the degree of internal salinization below the mound will increase by the continuous activities of the termites; Andropogon greenwayi disappears from the mounds. Also the area affected by salinization will increase. Increase of subsoil salinity and of the salt-affected area is likely to be reflected by a further retreat of the Andropogon greenwayi grass cover. This stage is represented by the situation found in the NaNo VI-IX transect.
Once the mounds have become uninhabited, a process of degradation will start: second stage of the cycle. Gradually the mounds will obtain a flattened shape due to levelling; their diameter, at the other hand, will increase. The beginning of this stage is represented in the NaNo I-V transect. The levelling of the mounds can largely be attributed to accelerated erosion processes due to the activities of wild animals - such as seraping with their hoofs and digging in combination with rainfall.

During the process of levelling, the salts, that had accumulated near the centre of the mounds, will spread over a larger area by pedogenetic processes described before. The concentration of the free salts in the subsoil will become lower.
The final stage of the cycle is reached when the mounds have become completely levelled. This situation may be represented, for instance, by situations like the NaNo-A (Andropogon greenwayi spot) and the adjacent NaNo-B (Digitaria macroblephara) spots, which lay at one level.

The A-profile was salt-free while the B-profile was still strongly saline below 50 cm. From this stage the salts in the B-profile will gradually be leached downwards and Andropogon greenwayi would get a chance to invade. The latter phenomenon has, in fact, been recorded: small Andropogon patches extending from the A-spots into the B-spots while also small isolated spots within the Digitaria spots (B-spots) were found. When the B-spot has changed into an Andropogon greenwayi spot, the cycle may start again when termites start building another mound. No information is available about the space of time for one complete cycle.
Other sites within the Andropogon greenwayi grassland for which the above processes are thought to be relevant are the following: NaNo-Flank A & B spots, HiVa-K-south-west A and B spots, Oldoinyo Olobaie-A and B spots.

In the area east and south of Naabi Hill many hyena dens and warthog holes were found; some had a single entrance and exit, many others had several entrances. Most of these places were marked by a low hill that consisted of thrown out subsoil material. The hills'shapes and dimensions varied strongly with the size and age of the den. Old dens and burrows had become levelled and covered areas up to 10 metres across. Like in the case of the termite mounds, also these spots were marked by vegetation types that differed strongly from the surrounding type, in which Andropogon greenwayi was mostly the dominant species. The effects of these dens on the chemical situation of the surrounding soils have not been studied but they are estimated to be less radical than those caused by termites or to occur over shorter periods of time.

4 . Soil Classification

4 .1. General

The soils were classified according to Soil Taxonomy of the U.S.D.A. (1975). In this classification system, the so-called soil moisture and soil temperature regimes form - in addition to the various diagnostic surface and subsurface horizons distinguished - important criteria for the classification on the highest levels.
On the changes of the soil moisture contents in the moisture control section during the year, and on the soil temperature no accurate data were available. With the help of the rainfall data from stations throughout the study area and measurements of the maximum and minimum air temperatures made at the Serengeti Research Institute, estimations on the soil moisture and temperature regime have been made (see also Part I, Ch. 3: Climate):

- Soil temperature: Since the study area is located close to the equator (appr. $2^{o}30'$ south latitude), the mean seasonal fluctuations of the soil temperature at a depth of 50 cm can be expected to be within 5^{o} C. The mean annual temperature was estimated lower than 22^{o}C because of the high elevation of the area (1500-1800 m above sea level). The soil temperature regime has therefore been characterized by the term Isothermic.
- Soil moisture: From 10 year monthly rainfall records it appeared that some part of the soil moisture control section is likely to be continuously moist for at least 90 consecutive days (wet season lasts from November till June) and to be dry for more than 90 cumulative days (mainly during the dry season between June and November) in most years (i.e. 7 out of 10 years). The moisture regime can therefore be called Ustic.

In the eastern part of the study area, viz. the area east and south-east of the Park boundary, which has the lowest mean annual rainfall (see Part I Ch. 3: Climate), the moisture regime may locally grade into an aridic moisture regime, e.g. in eroded soils with a petrocalcic horizon within 10 cm from the soil surface and in soils with a strongly developed surface crust (usually soils with sparse grass cover). Aridic moisture regimes at a higher mean annual rainfall might also occur in very shallow soils of "kopjes", quartz hills and eroded valley walls. Aquic and peraquic moisture regimes will occur in swamps and the mud flats that surround the soda lakes (e.g. Lake Ndutu). Udic moisture regime may occur in poorly drained soils, e.g. in some marshy spots on ridge tops and in some heavy clayey valley bottom soils in the western and north-western part of the Serengeti Plain. In general, soils that may have moisture regimes other than ustic, belong to the Miscellaneous landtypes and cover only a minor part of the study area.

Characteristic for nearly all the soils of the grass covered Serengeti Plain (broad soil landscape I: Sediment Plain) is the presence of a mollic epipedon which is shown by the following data:

a. The epipedons have dark grayish brown to black colours: 10 YR 4-5/2-3 when dry, 10 YR 3/2-3 when moist in the eastern parts, to 3-5/1-2 when dry and 10 YR 2-3/1-2 when moist in the western and north-western parts of the plain. The dark colour are not only due to the fairly high contents in organic matter but also to the high percentage dark coloured heavy minerals (mainly augites) in these soils.
b. Organic matter contents up to 5% were found in the top soils of the Short grasslands (following the method according to Kurmies, 1949). The contents are probably even higher in the

top soils of the Andropogon greenwayi grasslands but lower in those of the Long grasslands. The estimations of the humus contents by measuring the loss of weight on ignition ("Oosterbeek" method, results given in Appendices 19 and 34

are probably highly inaccurate - i.e. too high - because of the interference caused by the dehydration of amorphous materials or zeolites, which occur in substantial amounts in these soils; especially the figures obtained from C-horizon samples may suffer from this inaccuracy.

c. Base saturation in the epipedon area is over 50% throughout the study area: 100% in the eastern parts, gradually decreasing to 80% in the western and north-western parts.

d. Soil structures in the epipedons are not massive and hard or very hard when dry and the diameters of prisms or columns never exceed 30 cm.

e. Thickness of the epipedon is sufficient to be a mollic (eastern, central and western parts), or the surface horizon - after the soil is mixed to a depth of 18 cm - meets all requirements of a mollic epipedon except thickness, and the underlying soil (over 7.5 cm thick) forms part of an argillic or a natric horizon which meets all requirements of a mollic epipedon.

f. In most epipedons the amounts of phosphorus soluble in citric acid are less than 250 ppm; this excludes the epipedons from the Anthropic epipedon. For the cases in which the phosphorus contents exceed the limit of 250 ppm (e.g. GT III, NaNo-A), it would be difficult to identify them as Anthropic epipedons since these high contents are not the result of human activity in the past; the wolcanic ash itself appeared to be rich in anorganic phosphorus compounds (Apatite): Anderson and Talbot (1965) mention total P-contents up to 10.000 ppm in juvenile volcanic ash soils in the eastern part of the Plain.

Although the exchange complex of most of the soils of the Sediment Plain is dominated by amorphous materials, bulk densities were higher than 0.85 g/cm^3 while the fine earth fraction seems to contain little or no vitric volcanic ash[1]), cinders or vitric pyroclastic materials. This makes it possible to include the soils of the Sediment Plain in the Mollisols, although the soils' origin and some of their physical-chemical properties like thixotropy and pH-dependent cation exchange capacity, strongly remind of the former Andosols or Andepts (Inceptisols) according to Soil Taxonomy (1975). This especially applies to the weakly developed soils of the Short grasslands.
The characteristics of the more clayey soils of the western and north-western parts of the plain that include the greater parts of respectively the Andropogon greenwayi and the Long grasslands, do not show the combination of soil horizons more than 50 cm thick with more than 35% clay and a COLE of 0.07 or more (Ustic moisture regime!) and cracks of some periods in most years that are 1 cm or more wide at a depth of 50 cm; soil layers with a thickness of 25 cm or more that have more than 35% clay with montmorillonitic mineralogy or with COLE of 0.07 or more in combination with a lithic or paralithic contact within a depth of 50 cm do also not occur.
For these reasons the clayey soils of the western and north-western parts of the Sediment Plain have also been classified as Mollisols instead of Inceptisols.

[1]) After completion of this study (1978), the true nature of an important part of the mineral fractions of these soils is still unknown.

Because the moisture regime throughout the study area has been defined as Ustic, most soils fit in the suborder of Ustolls. In valley bottoms in the areas just mentioned, the soils have cracks of over 1 cm wide at 50 cm depth, a COLE of 0.07 or more, clay contents far over 35% (with traces of montmorillonitic mineralogy) but also slickensides; these soil fall in the order of Vertisols, suborder Usterts.

4.2. Classification of standard profiles

In the following the various Great Groups and Subgroups that have been distinguished within the Soil Landscapes I.1 (Short grasslands), I.2 (Andropogon greenwayi grasslands) and I.3 (Long grasslands) are discussed.

- Soil Landscape I.1: Short grasslands

The soils in the eastern part of the Serengeti Plain are calcareous up to the surface; most have a petrocalcic horizon or a calcic horizon within the upper 1.0 metre. They can be classified in the Great Group of Calciustolls. The dominant subgroup is the Petrocalcic Calciustoll: in the easternmost parts of the study area the petrocalcic horizon occurs usually within the upper 50 cm of the profiles, both on the ridges, the flanks and in the valleys. On the family level the class "shallow" applies to these soils.

In places where the petrocalcic horizon occurs at a very shallow depth, e.g. at eroded sites, intergrades to aridisols (aridic moisture regime, thin epipedons) may occur: Aridic Petrocalcic Calciustolls (or Paleorthidic Calciustoll).

Towards the west, the depth at which a petrocalcic horizon is found, was gradually increasing. Petrocalcic Calciustolls were found only on the ridge tops and upper parts of the flanks (e.g. in the BARSEK profile). Ridge, flank and valley bottom soils with petrocalcic horizon deeper than 1 metre or without a petrocalcic horizon (valley bottoms!) can be classified as Typic Calciustolls. In deep valleys, within the same part of the study area, that receive much water from the flanks, decalcification of the top soil has taken place (e.g. in the SEK-NE profile); these soils are to be classified as Haplustolls; depending on the thickness of the mollic epipedon Cumulic (SEK-NE) and Typic Haplustolls can be distinguished.

Further west and north-westwards also the top soils of the ridges and flanks have become decalcified. The depths to which the ridge soils have been decalcified correspond well with the increase of the mean annual rainfall from the east towards the west (positive correlation).

Beside the regional gradient in decalcification, there is also a catenary gradient: the thickness of the non-calcareous top layer increases down the slope to 1 metre or more in the valley bottoms. The ridge top soils grade from Petrocalcic Calciustolls in the east to Petrocalcic Paleustolls in the north-west near the boundary with the Long grasslands.

Soils of the flanks and valley bottoms are Typic Haplustolls or Pachic Haplustolls if there are very thick epipedons ($>$50 cm) or Cumulic Haplustolls if there is no gradual decrease of the organic carbon content to a value of 0.3% or less at 1.25 metres; the two latter subgroups will especially occur in the valleys.

Soils that have a salic horizon - they occur commonly in the so-called step-erosion area (A.4 area) and as "bare" or slick spots in various other parts of the Short grasslands - may be classified as Salorthidic Calciustolls - which would be a new subgroup since Soil Taxonomy does not mention salic or salorthidic Subgroups within the Great Group of Calciustolls - or as Salorthidic Haplustolls in soils with a decalcified top soil and a salic horizon at lower depth. The latter taxon is not common since internally salt-affected soils seldom had salt contents of over 2.0%, while soils marked by external salinization are mostly calcareous up to the surface - even if they occur within the zone in which a significant decalcification is found - because calcium and magnesium ions, transported by run-off and subsurface transport, are precipitated as calcium and magnesium carbonates by the free sodium carbonate, which forms usually an important component of the salt composition in the soils in this part of the study area. Many soils of the flanks within the "Short grasslands" area are moderately or strongly salt-affected (ECe>8 resp. 16 mmhos/cm) within a depth of 50-100 cm; in the classification this has been indicated by the addition "saline phase".

On the family level the "Short grassland" soils can be well defined as thixotropic and isothermic; if a petrocalcic horizon occurs within a depth of 50 cm the adjective shallow can be added; the term thixotropic covers both particle size and mineralogy class.

In case the soils would be included in an Andeptic subgroup - which seems very appropriate in view of the volcanic origin of these soils and consequently their physical-chemical properties and mineralogical composition - the term thixotropic can be omitted: Eutrandeptic petrocalcic calciustoll, Eutrandeptic Haplustoll etc.

Under the BARSEK profile (Appendix 3) it has been pointed out that classification of the Short grassland soils as Inceptisols, viz. Eutrandepts (Petrocalcic calciustollic or Haplustollic

Eutrandepts) encountered difficulties, of which the too high bulk densities (over 0.85 g/cm^3) were the most relevant; a few values, however, were very close to the limit of 0.85.

- Soil Landscape I.2: Andropogon greenwayi grasslands

With the further increase of the mean annual rainfall the decalcification of the top soil has progressed till a greater depth: 40-50 cm on the ridges to depths of over 1 metre on the flanks and the valley bottoms. The more intensive leaching processes in association with higher organic matter contents and an increased level of biological activity (termites and also earthworms!) have resulted into a stronger degree of transformation of mica's and, possibly, also of amorphous material into clay minerals with swelling properties: soil structure has become more developed, with cracks between structural elements and COLE values up to 0.023 were found; a petrocalcic horizon is lacking, but below a depth of 1 metre weakly cemented very coarse lumps of soil material rich in lime were found (ridge top soils). The ridge top soils have been classified as Typic Haplustolls; there were two phases: a non-saline one, which occurred under a vegetation cover of Andropogon greenwayi and a saline one - internal salinization, likely to be the result of termite activity - which was found under a sparse grass cover mainly consisting of Digitaria macroblephara, Pennisetum stramineum and Cynodon dactylon. The dark top soil of the non-saline phase had the most strongly developed soil structure and the highest COLE figures; these features have been expressed on the family level: fine, mixed, over thixotropic; the saline phase was defined as (fine, mixed over) thixotropic. Both profiles might be included in an Eutrandeptic subgroup; for the saline phase, which has much in common with the thixotropic soils in the Short grasslands this seems most appropriate.

Soils of the flanks with a textural B-horizon - they occur in central and western parts of the Andropogon greenwayi grasslands - may be classified as Argiustolls, the profiles that are salt-affected (probably also related with termite activity) as Natrustolls. In the westernmost parts of this soil landscape, the soils of the flanks and flat plain will grade towards Vertisols via Vertic Argiustolls or Vertic Haplustolls. The valley bottom soils change from Typic Haplustolls in the east via Vertic Haplustolls to Vertisols (Typic Pellusterts) in the central and western parts of the Andropogon greenwayi grasslands. On the family level the classes fine and very fine may be distinguished.

In the area between the Mbalageti valley and the Uplands in the west, external salinization is found in various places; these soils may be classified as Salorthidic Haplustolls. Soils that receive more moisture because of their relief position - e.g. imperfectly drained parts of the flat plain in the area just mentioned - may have an Udic moisture regime, which would result into the following taxons: Udic Haplustoll, Udertic Haplustolls and, in the depressions, Udic Pellusterts, with on the family level the classes fine or very fine.

- Soil Landscape I.3 (Long grasslands)

In the eastern and south-eastern parts the taxa are roughly the same as those found in the adjacent Short grasslands. The ridge tops have a non-calcareous top soil of which the thickness varies from 30 cm in the south-east to appr. 1 metre in the north-western corner of the Long grasslands. Except for the ridge soils in the north-westernmost part, the ridge top soils had a petrocalcic horizon within a depth of 1.5 metres, mostly at a depth of about 1 metre. According to Soil Taxonomy (1975) these profiles have to be included in the great group of Paleustolls; following the destinctions between Typic Paleustolls and other subgroups, the soils can be classified as Petrocalcic Paleustolls (without argillic horizon!).

In view of the similarity in morphology and physical-chemical properties between the soils of the Short grasslands and those of the ridge tops in the Long grasslands, it would be appropriate to include also the latter soils in an Andeptic subgroup: Eutrandeptic Petrocalcic Paleustoll. The bulk densities of the Long grassland ridge top soils are well over 1.00; classification as an Eutrandept (Petrocalcic Paleustollic Eutrandept?) seems not appropriate. On the family level the profiles can be characterized as thixotropic, isothermic, or in case they are included in an Andeptic subgroup as isothermic only.

On some ridges in the south-eastern part, external salinization is found at the base of so-called erosion scarps. In case a salic horizon occurs the profiles might be classified as Salorthidic Calciustolls (calcareous soils; not mentioned in Soil Taxonomy) or Salorthidic Haplustolls (soils with a decalcified top layer; a fluctuating groundwater tabel, as mentioned for this taxon in Soil Taxonomy, was absent).

On the flanks the following taxa have been distinguished: Typic or Vertic Argiustolls (Haplustolls in case there is no argillic horizon) coinciding with "Long" grass spots, and Typic Natrustolls in places where "short" grasses are found (mosaics of "short" and "long" grass spots!).

The B-horizons of the flank soils have high clay contents and overlie a loamy substratum (C-horizon); the B-horizon material has no marked thixotropic properties; the C-horizon material resembles that of the ridge top profile. Judged from the diffractograms and the COLE values (Table 23), well crystallized clay minerals e.g. montmorillonite, constitute certainly less than 50% of the total clay fraction, in which case the mineralogy is characterized by the term "mixed" mineralogy. On the family level the flank profiles can be classified as fine or very fine, mixed, over thixotropic, isothermic. On the lower flanks vertic properties were more pronounced, although cracks, that are open to the surface, have not been recorded. In the valleys, the soils are nearly black and have wide cracks during the dry season; the cracks are partially filled up with loose granules (self-mulch). Clay percentages in the A-horizon are very high (70%); in the C-horizon the soil has a loamy texture and shows resemblance with C-horizon material of the flank soils. In the lower part of the A-horizon coarse slickensides are common. The soils have all the characteristics of a vertisol: Typic Pellustert, very fine over thixotropic, isothermic. Locally, udic moisture regimes may occur, for instance in the Moru area near places where springs, originating at the base of some kopjes, supply extra amounts of water, even for some time after the wet season has ended.

The most common Miscellaneous land type within the Long grasslands are the Kopje associations (IV.3). Depending on soil depth various subgroups of Mollisols may be distinguished such as Cumulic Haplustolls and Typic Haplustolls (deeper soils of the kopje pediments), Lithic Haplustolls (shallow kopje soils).

- Broad soil landscape II: Dissected Plain (woodlands)

In the eastern part - i.e. east of the Ngare Nanyuki airstrip (see Fig.2b) - the soils have been strongly influenced by volcanic ash: soil landscape II.1. The ridge soils, that support a vegetation of short grasses, resemble those in the adjacent parts of the Sediment Plain. The upper 20-40 cm are non-calcareous while a petrocalcic horizon occurs within 1.50 metres; in places marked by erosion even within 50 cm. Internal salinization has been recorded locally (saline phases).
The ridge soils can be classified as Petrocalcic Paleustolls, or, to emphasize the volcanic nature, as Eutrandeptic Petrocalcic Paleustolls. On the family level the term "shallow" is applicable locally (eroded soils). The soils of the flanks and valley bottoms - these units are covered by wooded grassland - were fine-textured (clayey) whereas in the Sediment Plain loamy textures predominated in soils of corresponding relief positions. Calcic horizons do occur within 1.0 m (flanks); salinity may occur below a depth of 1 metre. For soils of the flanks and valley bottoms within soil landscape II.1. the following taxa may be distinguished:

- Typic Haplustoll: decalcified top soil, without an argillic horizon (flanks);
- Typic Argiustoll: decalcified top soil, with an argillic horizon and
- Typic Natrustoll in case there is a natric horizon (mosaics of short and long grass spots!).

The Argiustolls and Natrustolls are more likely to occur in the western part of the soil landscape II.2, the Haplüstolls and Paleustolls in the eastern part.

In soil landscape II.2, north-west of the Ngare Nanyuki airstrip, the volcanic influence gradually decreases; the soils have for the greater part derived from basement-rock material. The top soils, however, still have very dark colours and their characteristics fit the requirements of a mollic epipedon. In this area the ridgetops are covered by woodland, the flanks by long grassland or very open woodland, while the drainage lines are marked again by the presence of trees. In the surroundings of the village of Seronera and the Research Institute the ridge soils had no petrocalcic horizons; a lithic contact was mostly found within 1.50 metre. In case the bed-rock occurred within 50 cm the soils can be classified as Lithic Haplustolls and profiles with bedrocks deeper than 50 cm as Cumulic or Pachic Haplustolls. Although the soils have been influenced by volcanic ash (amorphous material still forms a part of the exchange complex, but not to the extent as found for the ridge soils in the east: II.1), it would not be correct to include these soils in an Andeptic subgroup.

On the flanks, mosaics of "short" and "long" grass spots are found; in places, also trees occur. The "short grass" soils had invariably the highest concentrations of soluble salts coinciding with the presence of a natric horizon; most of the "short grass" profiles can be classified as Typic Natrustolls, fine, mixed, isothermic, e.g. the SRI 3 profile (see Appendix 44[1]). In the profiles evidence for temporary wetness was found: manganese concretions (fine, spherical) and faint reddish mottling (iron).

Soil Taxonomy (1975) does not mention Aquic subgroups within the great group of Natrustolls, but it might be appropriate to apply such a subgroup to the "short grass" soils within this area. The "long grass" soils had low salt contents (non-saline throughout) but natric horizons may occur, e.g. in the SRI 2 profile Typic Natrustoll: ESP over 15 as a result of relatively high amounts of soluble sodium.
In the latter case the structural elements in the B-horizon were not columnar but prismatic; it would make sense to distinguish a columnar and a prismatic phase within the Typic subgroup.
Other "long spot" profiles will fit the great group of Argiustolls and, if there is no argillic horizon, that of Haplustolls. Several profiles showed characteristics of a Vertic subgroup, viz. cracks of 1 cm wide at 50 cm, high clay contents possibly in combination with COLE values of 0.07 or more (not measured): Vertic Argiustolls and Vertic Haplustolls, fine or very fine, mixed, isethermic.
In the direct surroundings of isolated kopjes and in places with basement rock within a depth of 50 cm, Lithic subgroups may be distinguished.
In the valley bottoms the profiles showed only a moderate horizon differentiation. They are finely textures and have cracks over 1 cm wide within the upper 1 metre, but, contrary to the situations in the valley bottoms in the Andropogon greenwayi and Long grasslands of the Sediment Plain, diagnostic properties of a vertisol like slickensides are lacking. Therefore the soils have to be classified as Vertic Haplustolls.

4.3. Conclusions and Discussion

All soils of the Sediment Plain (broad soil landscape I or Serengeti Plain) and of the Dissected Plain (woodlands) have been classified as Mollisols, except for the soils of some valley bottoms in the western and north-western part of the Sediment Plain, which could be characterized as Vertisols.

It has already been pointed out that many soils are intergrades between Mollisols (suborder Ustolls; great groups: Calciustolls, Haplustolls and Paleustolls) and Inceptisols: viz. Eutrandepts (parent material is volcanic ash, high base saturation throughout the profiles).

Most important in this respect are the soils of:

1. The Short grasslands (soil landscape I.1), except for Miscellaneous landtypes;
2. The eastern part of the <u>Andropogon greenwayi</u> grasslands (i.e. east of Naabi Hill) as well as soils of ridge tops in other parts of this soil landscape (I.2);
3. Ridges and ridge tops in the Long grasslands (soil landscape I.3) and
4. Ridges in the eastern part of the Dissected Plain (soil landscape II.1).

The mean reason for excluding these soils from the Andepts (Inceptisols) were the too high bulk density values.

Because the bulk density in most of the soils exceeds 0.95 g/cm^3, it is also not possible to include them in Andeptic subgroups.

Soils with thixotropic properties (i.e. most soils of the Short grasslands and the eastern half of the <u>Andropogon greenwayi</u> grasslands) can be separated from the rest by including them in thixotropic families.

This is not very satisfactory and a revision of the Andeptic subgroups and, perhaps, also of the great group of Andepts seems necessary.

A further advanced stage of soil formation is represented by the <u>Natrustolls</u> and <u>Argiustolls</u>, that include the soils of the flanks within the Long grasslands, <u>Andropogon greenwayi</u> grasslands and the eastern part of the Dissected Plain (II.1). The volcanic origin of the parent material of these soils is still evident (amorphous material dominates or forms an important part of the exchange complex, high contents of heavy minerals) and also for these soils it might make sense to include them in an <u>Andeptic</u> subgroup.

Using an <u>Andeptic</u> subgroup the therm "thixotropic" can be left out on the family level.

The soils of the western part of the Dissected Plain still belong to the Mollisols, but contain only small contents of ash (except for those of some broad flat ridgetops which lie near the boundary between the Dissected and the Sediment Plain); <u>Andeptic</u> subgroups do not apply to these soils any longer.

Applying the above to the taxonomic classification, both the gradual increase of profiles development in the Sediment Plain from the east towards the west and the nature of the parent material - volcanic ash or residual materials from the Pre-Cambrian basement - can be roughly deduced from the names of the taxa distinguished. In this respect the subgroups that have been distinguished within the great group of Ustolls in Soil Taxonomy (1975) would give a less clear picture.

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Appendices

Appendices, available at the Dept.of Tropical Soil Science, Agricultural University, Wageningen, Holland, are:
Nrs. 2, 7, 8, 9, 11, 12, 14, 15, 20, 21, 24, 25, 26, 27, 32, 33, 35, 38, 40, 42, 44.

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Appendix 1

Summary of daily cumulative falls in six classes at the SRI for each month; seasonal, annual and 3-year totals.

	daily cumulative falls of																	
	0–5 mm			5–10 mm			10–15 mm			15–20 mm			20–25 mm			≥25 mm		
	N[1]	Σ[2]	%[3]	N[1]	Σ[2]	%[3]	N[1]	Σ[2]	%[3]	N[1]	Σ[2]	%[3]	N[1]	Σ[2]	%[3]	N[1]	Σ[2]	%[3]
Nov.1970	5	10.2	20.1	3	19.5	38.5	-	-	-	-	-	-	1	21.0	41.4	-	-	-
Dec. "	7	9.3	10.2	3	24.0	26.2	2	21.1	23.1	2	37.1	40.5	-	-	-	-	-	-
Jan.1971	5	2.0	4.1	4	27.8	56.6	-	-	-	1	19.3	39.3	-	-	-	-	-	-
Febr. "	6	10.0	14.7	3	17.3	25.5	-	-	-	-	-	-	-	-	-	1	40.5	59.7
March "	3	0.8	3.4	-	-	-	-	-	-	-	-	-	1	22.6	96.6	-	-	-
April "	10	14.7	5.5	4	30.4	11.4	1	11.6	4.4	1	19.5	7.3	1	23.7	8.9	3	166.6	62.5
May "	6	7.6	8.4	2	15.4	17.1	-	-	-	1	18.3	20.3	1	21.0	23.3	1	27.7	30.8
June "	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
July "	3	9.2	38.8	-	-	-	1	14.5	61.2	-	-	-	-	-	-	-	-	-
Aug. "	7	18.3	16.4	-	-	-	1	12.5	11.2	1	17.1	15.3	-	-	-	2	63.6	57.0
Sept. "	7	6.6	100.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Oct. "	5	5.6	5.5	1	7.3	7.2	1	14.4	14.2	-	-	-	-	-	-	1	74.3	73.1
wet season	42	54.6	8.5	19	134.4	21.0	3	32.7	5.1	5	94.2	14.7	4	88.3	13.8	5	234.8	36.7
dry season	22	39.7	16.3	1	7.3	3.0	3	41.4	17.0	1	17.1	7.0	-	-	-	3	137.9	56.7
total	64	94.3	10.7	20	141.7	16.1	6	74.1	8.4	6	111.3	12.6	4	88.3	10.0	8	372.7	42.2
Nov.1971	5	7.2	12.5	-	-	-	-	-	-	-	-	-	1	24.4	42.3	1	26.1	45.2
Dec. "	8	16.1	21.1	3	19.1	25.1	1	14.5	19.0	-	-	-	-	-	-	1	26.5	34.8
Jan.1972	7	17.0	53.1	2	15.0	46.9	-	-	-	-	-	-	-	-	-	-	-	-
Febr. "	5	9.5	6.8	2	13.2	9.4	1	11.8	8.4	-	-	-	1	24.5	17.5	2	81.1	57.9
March "	7	6.2	9.8	2	12.2	19.1	1	13.1	20.7	-	-	-	-	-	-	1	32.0	50.5
April "	1	1.9	2.2	-	-	-	-	-	-	1	15.4	18.0	1	21.0	24.5	1	47.3	55.3
May "	2	5.0	5.3	1	7.4	7.8	-	-	-	-	-	-	2	41.7	44.0	1	40.6	42.9
June "	9	4.8	3.9	1	6.4	5.2	1	10.3	8.3	-	-	-	2	46.3	37.3	2	56.2	45.3
July "	1	0.1	100.0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Aug. "	4	8.0	11.1	1	8.9	12.4	1	12.9	18.0	1	16.8	23.4	-	-	-	1	25.2	35.1
Sept. "	2	7.9	10.5	-	-	-	-	-	-	-	-	-	1	21.6	28.6	1	45.9	60.9
Oct. "	8	15.8	31.3	2	12.2	24.2	2	22.5	44.5	-	-	-	-	-	-	-	-	-
wet season	35	62.9	11.4	10	66.9	12.2	3	39.4	7.2	1	15.4	2.8	5	111.6	20.3	7	253.6	46.1
dry season	24	36.6	11.4	4	27.5	8.6	4	45.7	14.2	1	16.8	5.2	3	67.9	21.1	4	127.3	39.6
total	59	99.5	11.4	14	94.4	10.8	7	85.1	9.8	2	32.2	3.7	8	179.5	20.6	11	380.9	43.7
Nov.1972	9	18.4	9.9	1	7.3	3.9	1	10.3	5.5	2	33.3	17.9	1	23.5	12.6	2	93.3	50.1
Dec. "	2	6.2	3.1	3	18.0	9.1	3	35.6	18.0	1	18.0	9.1	1	20.3	10.3	3	99.7	50.4
Jan.1973	7	9.1	10.7	-	-	-	4	49.9	58.9	-	-	-	-	-	-	1	25.7	30.3
Febr. "	7	11.1	15.5	2	14.3	20.0	2	27.8	38.9	1	18.3	25.6	-	-	-	-	-	-
March "	5	7.7	100.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
April "	7	13.9	29.3	2	14.5	30.6	-	-	-	1	19.0	40.1	-	-	-	-	-	-
May "	5	6.8	9.0	2	14.5	19.2	3	37.6	49.7	1	16.7	22.1	-	-	-	-	-	-
June "	2	2.0	10.2	1	7.3	37.2	1	10.3	52.6	-	-	-	-	-	-	-	-	-
July "	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Aug. "	3	5.0	37.6	1	8.3	62.4	-	-	-	-	-	-	-	-	-	-	-	-
Sept. "	7	10.1	5.8	1	7.0	4.0	1	12.5	7.2	1	18.2	10.5	3	65.5	37.9	2	59.6	34.5
Oct. "	3	1.5	8.4	3	16.4	91.6	-	-	-	-	-	-	-	-	-	-	-	-
wet season	42	73.2	10.9	10	68.6	10.2	13	161.2	24.0	6	105.3	15.7	2	43.8	6.5	6	218.7	32.6
dry season	15	18.6	8.3	6	39.0	17.4	2	22.8	10.2	1	18.2	8.1	3	65.5	29.3	2	59.6	26.6
total	57	91.8	10.3	16	107.6	12.0	15	184.0	20.6	7	123.5	13.8	5	109.3	12.2	8	278.3	31.1
tot.wet s.	119	190.7	10.3	39	269.8	14.5	19	233.3	12.6	12	214.9	11.6	11	243.8	13.1	18	707.1	38.0
tot.dry s.	61	94.9	12.0	11	73.8	9.4	9	109.9	13.9	3	52.1	6.6	6	133.4	16.9	9	324.8	41.2
total (1970–1973)	180	285.6	10.8	50	343.6	13.0	28	343.2	13.0	15	267.0	10.1	17	377.2	14.2	27	1031.9	39.0

1) N : number of daily records

2) Σ : sum of monthly, annual or 3-year rainfall

3) % percentage of monthly, annual or 3-year rainfall

Profile no. 44 (BARSEK)

GENERAL DATA

Area: Lemuta; BARSEK plot
Location: about 9700 N 746 E (1 : 250 000 Serengeti map)
Elevation: ca 1750 m.
Described by: H.A. de Wit
Date: 12-7-1973
Wheather condition: bright, dry during last 2 months
Aerial photo: L 13 S 7-65 Ser. Jan 1972 (Finn Map)
L 14 S 2-107 Ser. Jan 1972 (Finn Map)
Physiography: flat plain, aeolian origin
Topography: flat
Slope: class A, level
Erosion: none; waterhole with few erosion steps 1 km towards the west
Parent material: volcanic ash (calcareous loam)
Landuse: Nat.Park for over 10 years
Vegetation 1): "Short" grassland; dominant and co-dominant species:
Smar, Sfim, Dima, Eupa, Miku, Disc, Kyllnerv, Melhovat
Drainage condition: well to somewhat excessively drained
Groundwater depth: none or very deep
Permeability: moderate at the surface, rapid below the surface
Moisture: dry - slightly moist 0-70 cm; moist below 90 cm
Salinity: non-saline 0-40, moderately saline 40-50, strongly saline below 50 cm; strongly alkaline below 30 cm
Stoniness: Class 0
Root distribution: abundant to many fine roots between 0-70 cm
Biological activity: few medium holes up to 2 inch diameter in 0-70 cm part, small termites and yellow ants present
Human activity: cattle ranching by Masai in the past
Pans: petrocalcic horizon at 70 cm depth

1) for abbreviations of species names see Appendix 47 and Part I, Ch 2: Methods

PROFILE DESCRIPTION

A 1.1 0-25 cm; 10 YR 4.5/2.5 when dry, 10 YR 3/2.5 when moist, calcareous loam; moderate medium and coarse subangular blocky when disturbed, locally tending to be prismatic, peds or clods often attached to roots, medium thick or thick platy at the surface (crust); soft when dry, very friable when moist, non to slightly sticky and slightly plastic when wet; few large, common medium and fine biopores, many micropores; few medium, many fine roots; few fine and medium weakly cemented dung beetle balls or parts of them; lower boundary clear and slightly wavy.

A 1.2 25-45 cm; 10 YR 5/3 when dry, 10 YR 3/3 when moist, calcareous loam; weak coarse and very coarse subangular blocky; soft when dry, very friable when moist, non sticky andslightly plastic when wet; few meso and fine biopores, many micropores; many fine roots; lower boundary gradual and smooth.

AC weak 45-60 cm; 10 YR 6/3 when dry, 10 YR 4/3 when moist calcareous loam; very coarse and very coarse crumb (almost single grain when disturbed); soft when dry, very friable when moist, non-sticky and almost non-plastic when wet; very porous material; many fine roots; few above and common below, fine and medium weakly cemented porous soil parts, subangular shaped, hard when dry, firm when moist; lower boundary clear and smooth.

C 60-70 cm; 10 YR 6/3 when dry, 10 YR 4/3 when moist, calcareous loam; mixture of structureless, single grain and medium and coarse weakly cemented clods, concretion-like; almost loose when dry, loose to very friable when moist, non-sticky and almost non-plastic when wet; cemented clods hard when dry, friable when moist; common, locally many fine roots; lower boundary abrupt and smooth, locally irregular.

C2m 70-105 cm; 10 YR 6/3.5 when dry, 10 YR 4/4 when moist, strongly cemented calcareous tuff, top 5-10 cm indurated (10 YR 3/2-4/2), partially vesicular on top; indurated part ("hardpan") not breakable by hand, only by hammer; strongly cemented lower part is hard to break by hand but softens when moistened (breakable by hand); no roots; very porous, also common fine old biopores (rootholes), few large pores; white veins, often on the inner walls of the fine pores, few above, common below; lower boundary abrupt and wavy.

C 3 105-140 cm; 10 YR 6.5/4 when dry, 10 YR 4/4 when moist, silt loam; very weakly cemented calcareous tuff, non-sticky and non-plastic when wet; very porous; common fine white veins; common medium and coarse more strongly cemented parts, hard when dry; lower boundary abrupt and slightly wavy.

C 4 140-...; 10 YR 5/4 when dry, 4/4 when moist when broken, 10 YR 6/4 when dry, 4/4 when moist when rubbed, weakly, partially strongly cemented tuff; (v.) hard when dry, firm or very firm when moist; very porous, also fine and medium pores; many, locally abundant fine and medium white veins (old root channels).

Classification according to Soil Taxonomy (1975) :

Diagnostic surface horizon:	Mollic epipedon
Diagnostic subsurface horizons:	-Cambic horizon -Calcic horizon (35-55cm) -Petrocalcic horizon (at 70 cm)
Other diagnostic characteristics:	-Exchange complex dominated by amorphous material and zeolites (chabazite) -Little or no vitric volcanic ash and pyroclastic materials
Soil moisture regime:	Ustic
Soil temperature regime:	Isothermic
Order:	Mollisols
Suborder:	Ustolls
Great group:	Calciustoll
Subgroup:	Petrocalcic calciustoll, saline phase
Family:	Thixotropic (calcareous), isothermic

Profile no. 45 (SEK-NE)

GENERAL DATA

Area: Lemuta
Location: 2,5 km NE of the South-east kopjes
Coordinates: 9690,5 N 738 E
Elevation: 1600 m
Described by: H.A.de Wit
Date: 19/25-7-73
Weather condition: bright, dry for at least 2 months
Aerial photo: L 13 S 7-66/67 Serengeti Jan 1972 (Finn Map)
Physiography: valley bottom
Topography: flat
Slope: class A, level
Erosion: none
Parent material: volcanic ash, clay loam
Landuse: National Park for over 10 years
Vegetation 1): Cyda 5, Dima 3-4, Sfim 3, Cpic 2, Hars 2, Erci 1, Kyllnerv 1; Hypofors 2, Sidovata 1, Euphinae 1, total cover grasses about 50%, total cover by Hypofors appr.20-25%; grasses all withered; Hypofors partially green, flowering
Drainage condition: well drained
Groundwater depth: not established, no groundwatertable or watertable very deep
Permeability: surface soil moderate
subsoil moderately rapid
Moisture: 0-40 cm dry, 40-200 cm slightly moist, moist below 200 cm
Stoniness: class 0
Salinity: non-saline 0-170 cm, slightly saline 170-190 cm, moderately saline below 190 cm
Root distribution: 0 to 200 cm, main mass between 0-70 cm
Biological activity: common dungbeetleballs up to 5 cm diameter,fresh or old, found at all depths between 0-100 cm; connection-tunnels with surface filled with very loosely packed soil material, sometimes partially open (resembling krotovinas); most run vertically; also small yellow ants and a few termites were observed (emerged from infiltration rings); few larvae.
Human activity: extensive cattle ranching by Masai in the past
Remark: Profile described about 1 week after the pit was dug; after 1 week many fine cracks -up to 1 mm wide- showed up, both horizontally and vertically, forming very large prisms, most of them becoming conspicious below 40 cm.

1) for abbreviations of species names and for explanation of cover values see Appendix 47 Part I, Ch.2: Methods.

PROFILE DESCRIPTION

A 1.1 0-16 cm; 10 YR 4,5/2,5 when dry, 10 YR 3/2 when moist, silty clay loam; moderate medium and coarse subangular blocky often attached to roots, locally medium and thick platy near the surface, thin surface crust always present; soft to slightly hard when dry, very friable when moist, slightly sticky and slightly plastic when wet; few large, common meso and fine biopores, many micropores; common medium, many fine roots; few shells or shell fragments; lower boundary clear and wavy.

A 1.2 16-40 cm; 10 YR 4-4,5/2 when dry, 10 YR 3/2 when moist, (silty) clay loam; almost structureless, massive, falling apart into moderately weak medium and coarse clods with much unaggregated material, soft when dry, very friable when moist, almost non-sticky and slightly plastic when wet; common fine biopores, many micropores; few old dungbeetleballs with weakly cemented walls; lower boundary gradual and smooth.

A 1.3 40-70 cm; 10 YR 4-4,5 /2 when dry, 10 YR 2,5-3/2 when moist, calcareous silty clay loam; moderately weak very coarse prismatic, falling apart into moderate very coarse subangular clods; soft to slightly hard when dry, very friable when moist; non-sticky (above) to slightly sticky (below) and slightly plastic; few large and meso, common fine biopores, many micropores; common fine roots; common fresh and old dung beetle balls, few shell fragments; few white coatings, non-calcareous,on inner walls of biopores, becoming more common below; lower boundary gradual and smooth.

A 1.4 70-110 cm; 10 YR 4,5/2,5 when dry, 10 YR 3/2,5 when moist silty clay loam; moderately weak very coarse prismatic, locally slightly tilted, especially near the lower boundary; very weakly cemented fine clods, increasing in number downwards.

C 110-170 cm (bottom of pit); 10 YR 5/3 when dry, 10 YR 3/3 when moist, calcareous silty clay loam; weak very coarse prismatic,elements tending to be slightly tilted below, falling apart in few angular clods and little unaggregated material; slightly hard when dry, (very) friable when moist, sticky and plastic when wet, stickiness and plasticity increasing downwards; few large and few meso biopores, common fine biopores, many macropores; common fine roots but less frequent than in overlying horizon, locally accumulating on the peds surfaces; common fine and medium non-calcareous white veins; common fine weakly cemented soil aggregates, becoming more frequent towards the bottom of the pit.

by auger:

170-190 cm; soil material becomes more yellow, 10 YR 5,5-6/3 when dry, 10 YR 3,5/3 when moist; many fine, weakly cemented soil aggregates, concretion-like; slightly sticky and plastic when wet, slightly saline.

190-210 cm; 10 YR 6/3,5 when dry, 10 YR 4/3 when moist, slightly sticky and slightly plastic when wet, moderately saline.

210-250 cm; 10 YR 6/3,5-4 when dry, 10 YR 4/4 when moist; slightly sticky and non to slightly plastic when wet; moderately saline; many fine weakly cemented soil aggregates.

Diagnostic surface horizon:	Mollic epipedon (thicker than 50 cm)
Diagnostic subsurface horizon:	Cambic horizon (weak), forming the lower part of and underlying the mollic epipedon.
Other diagnostic features:	Exchange complex dominated by amorphous materials.
Soil moisture regime:	Ustic
Soil temperature regime:	Isothermic
Order:	Mollisols
Suborder:	Ustolls
Great Group:	Haplustolls
Subgroup:	Cumulic Haplustoll (Eutrandeptic Cumulic Haplustoll 1))
Family:	thixotropic, isothermic

1) see chapter on classification

6

Soil Landscape I.1 (Short grasslands): mean infiltration rates (mm/h)

profile, depths (cm)	Exp.[1]	n[2]	mean infiltr. rate	lowest value	highest value	mm infiltr. (averages)
BARSEK						
Surface[3]	I	15	147.9	102.3	200.0	25
	II	15	70.2	59.6	96.8	25
	III	15	67.3	56.4	81.4	25
	IV	15	64.8	47.7	83.3	25
12,5 cm[3]	I	10	182.7	116.9	222.2	25
	II	10	90.7	60.6	117.6	25
	III	10	87.5	52.9	112.5	25
35 cm[3]	I	5	303.9	281.2	367.3	25
	II	5	137.1	116.9	171.4	25
	III	5	128.4	107.8	162.2	25
	IV	5	127.6	107.1	162.2	25
	V	5*	124.5	102.3	162.2	25
52,5 cm[3]	I	5	144.9	114.6	195.6	25
	II	5	100.4	84.1	121.6	25
	III	5	92.1	81.8	109.1	25
	IV	5	91.4	80.4	114.6	25
SEK-NE						
Surface[4]	I	10	61.7	40.3	90.4	25.7
	II	10	41.9	25.8	60.8	25.7
	III	10	41.9	24.4	63.7	25.7
	IV	10	42.8	26.2	66.1	25.7
Surface[3]	I'	9	120.5	69.8	171.4	25
	II'	9	74.6	42.5	102.3	25
	III'	9	72.0	42.3	95.2	25
	IV'	9	70.2	40.2	101.2	25

profile depths (cm)	Exp.[1]	n[2]	mean infiltr. rate	lowest value	highest value	mm infiltr. (averages)
SEK-NE (cont.)						
7,5 cm[4]	I	5	149.0	120.0	218.2	21.2
	II	5	75.0	60.8	92.3	21.2
	III	5	70.3	55.6	82.8	21.2
	IV	5	70.8	56.1	82.8	21.2
	V	5	71.9	57.3	82.8	21.2
	VI	5	73.1	58.7	87.3	21.2
52,5 cm[4]	I	6	151.0	108.4	212.9	24.4
	II	6	81.7	57.7	129.4	24.4
	III	6	75.8	54.9	116.5	24.4
	IV	6	74.6	54.2	111.9	24.4
125 cm[3]	I	4	117.7	68.1	195.6	23.5
	II	4	59.4	37.4	79.6	23.5
	III	4	57.7	32.6	82.2	23.5
	IV	4	56.0	32.2	77.3	23.5
"Zebra"kopjes						
Surface[4]	I	10	76.6	26.6	139.8	12.43
	II	10	28.5	9.9	42.8	12.43
	III	10	25.8	10.4	32.8	12.43
	IV	10*	27.1	10.4	36.1	12.43
Gol kopjes						
Enclosure						
Surface[4]	I	10	73.7	35.9	138.1	15.54
	II	10	28.9	17.6	38.9	15.54
	III	10	25.7	18.1	33.3	15.54
	IV	10	26.6	18.4	33.9	15.54

1) Number of infiltration experiment
2) Number of rings used
3) Infiltration rings hit into the soil
4) Infiltration rings pushed into the soil (standard method, using a car-jack)
* one figure lacking; last known value filled (infiltration rate assumed to have become constant)

Soguna (flank, near Soguna kopjes)

depth (cm)	SP	pH_p	pH_e	EC_e	Na^+	K^+	Ca^{2+}	Mg^{2+}	Ca^{2+}+ Mg^{2+}	Sum +	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2}	NO_3^-	Sum -	% Lime
				(mmho/cm)	all in meq/l (saturation extract)												
0-10	44.8	7.40	7.66	0.87	2.26	1.80			5.93	9.99	-	6.81	0.71	1.06	-	8.58	1.01
10-20	42.6	7.96	8.14	0.64	1.65	0.97			3.87	6.49	-	3.70	1.04	1.50	-	6.24	0.82
20-30 w	41.5	8.15	8.34	0.66	1.74	0.86			3.84	6.44	-	3.01	1.95	1.15	0.25	6.36	2.69
30-40	43.4	8.17	8.37	1.24	7.96	1.03			2.90	11.89	-	2.59	7.51	0.87	0.50	11.47	4.50
40-50	41.7	8.31	8.52	7.10	62.61	2.32			2.59	67.52	-	3.80	51.82	11.83	0.25	67.70	5.48
50-60	36.0	9.77	9.81	21.30	243.48	6.44			0.20	250.12	49.80	28.95	80.50	99.42	-	258.67	13.64
60-70	40.9	9.88	9.92	27.00	346.08	8.10			-	354.18	104.16	53.84	80.81	111.35	0.75	350.91	17.13
70-80	42.4	9.89	9.92	30.00	391.30	9.53			-	400.83	130.30	67.95	86.87	112.98	0.50	398.60	13.94
80-90	40.3	10.10	10.08	35.40	481.30	12.02			-	493.32	197.95	64.53	101.21	129.33	0.50	493.52	13.53
90-100	37.6	10.02	10.02	34.60	483.91	11.79			-	495.70	191.10	69.37	96.16	125.48	0.25	481.36	10.97

SEK-WE (valley, just west of South-east kopjes)

depth (cm)	SP	pH_p	pH_e	EC_e	Na^+	K^+	Ca^{2+}	Mg^{2+}	Ca^{2+}+ Mg^{2+}	Sum +	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2}	NO_3^-	Sum -	% Lime
0-10	54.0	7.59	7.80	0.90	1.59	1.46			6.63	9.68	-	7.64	0.64	0.42	0.25	8.95	0.81
10-20	50.5	8.13	8.32	0.61	1.52	0.90			3.47	5.89	-	2.46	0.30	0.42	3.00	6.18	2.17
20-30	47.4	8.28	8.44	0.49	1.57	0.79			2.69	5.05	-	2.70	0.20	0.52	2.00	5.42	4.72
30-40	44.0	8.63	8.83	1.82	16.52	1.13			4.85	22.50	0.55	11.10	1.25	8.49	2.00	23.39	6.98
40-50	42.6	9.79	9.84	11.20	123.91	4.60			0.20	128.71	30.50	36.21	27.27	38.17	1.50	133.65	8.57
50-60	46.3	10.03	10.03	29.40	386.09	11.46			-	397.55	157.69	66.29	68.89	117.02	0.50	410.39	10.72
60-70	44.7	10.11	10.09	33.60	426.52	11.55			-	438.07	171.39	62.97	72.12	135.10	0.25	441.83	10.25
70-80	42.4	10.14	10.14	32.00	440.87	11.55			-	452.42	170.56	72.73	66.87	139.23	0.25	449.64	13.67
80-90	43.3	10.10	10.11	30.00	399.13	11.49			-	410.62	154.79	73.14	59.49	127.40	0.25	415.07	14.46
90-100	42.4	10.03	10.03	30.40	408.26	11.65			-	419.91	146.07	79.37	62.42	133.65	0.75	422.26	16.43

7

8

Profile no.42 (Zebra Kopjes)

GENERAL DATA

Area: Sametu
Location: coordinates 9710 N, 733 E
Elevation: 1740 m
Described by: H.A. de Wit
Date: 5-12-1973
Weather condition: overcast, previous month fairly dry (less than 50 mm rain)
Aerial photo: 7-63 L 13-8 Serengeti Jan 1972 (Finn Map)
Physiography: aeolian plain
Topography: flat, near top of slightly convex hill
Slope: Class A (level and nearly level) long slopes (1%)
Erosion: none; some erosion steps down the hill towards the west
Parent material: volcanic ash, calcareous, loamy
Landuse: National Park for over 10 years
Vegetation 1) : "Short" grassland; dominant and co-dominant grass species: Smar, Dima, Pcol, Hars, Miku, Erau, Sfim
Drainage condition: well drained to somewhat excessively drained
Groundwater depth: no groundwatertable could be established, watertable absent or very deep
Permeability: moderate at the surface, more rapid below the surface
Moisture: -
Salinity: 0-90 cm non-saline, 90-100 cm slightly saline, 100-120 cm moderately saline; alkaline below 70 cm (Zebra K profile d.d. 2-6-1971); considerable variations were recorded: some nearby profiles were found to be slightly saline below 100 cm, others were strongly saline already at a depth of 60 cm
Stoniness: Class 0; some granitic outcrops (kopjes) within 1 km
Root distribution: main mass between 0 and 80 cm (abundant to common), very few at 140 cm (bottom of pit)
Biological activity: a single old dungbeetle ball (3 cm diameter) at 50 cm depth; harvesting-termite activity in direct surroundings (small heaps of finely cut grasses, mainly Hars)
Human activity: cattle ranching by Masaai in the past. Chipped piece of opal (flintstone) at various depth

1) for abbreviations used for species names see Appendix 47

PRO FILE DESCRIPTION

A 1 0-20 cm; 10 YR 5/3 when dry, 10 YR 3/3 when moist loam; weak medium subangular blocky structure; moderate fine subangular blocky in pockets attached to root system of grass clumps close to the surface; surface cal (thick platy); few large biopores, common meso biopores, many micropores; many fine roots; lower boundary clear and wavy.

AC 20-35 cm; 10 YR 5/3 when dry, 10 YR 3/3 when moist calcareous silt loam; very weak structures, almost structureless, loose when dry; very porous material, common fine roots; lower boundary gradual and wavy.

C 35-70 cm; 10 YR 5/2-2,5 when dry; 10 YR 3/2 when moist silt loam; structureless; very porous material; very hard fine and medium lime concretions, becoming common near lower boundary, few rounded fine and medium quartz pebbles; lower boundary clear and smooth.

C.2 70-120 cm; calcareous silt loam; lighter, more yellowish colours (higher values and chromas) than overlaying horizons; the 70-80 cm layer was rich in fine and medium lime concretions, more or less rounded; below 80 cm concretions are common; fewer roots.

Diagnostic surface horizon:	Mollic epipedon 0-35 cm
Diagnostic subsurface horizon:	Calcic horizon 60-100 cm
Soil moisture regime:	Ustic
Soil temperature regime:	Iso(hyper)thermic
Other diagnostic features:	exchange complex dominated by amorphous materials
Order:	Mollisols
Suborder:	Ustolls
Great Group:	Haplustoll
Sub Group:	Typic Haplustoll (Eutrandeptic Haplustoll 1))
Family:	thixotropic, isothermic

1) see chapter on Classification

<u>Zebra K</u> Sampled on 2-6-1971

depth	SP	pH_p	pH_e	EC_e	Na^+	K^+	CA^{2+}	Mg^{2+}	Ca+Mg	Sum +	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	HO_3^{2-}	Sum -	% Lime
0- 10	42.2	7.08	8.10	0.84	1.17	2.07	3.54		4.88	8.12	-	4.70	0.23	0.29	3.00	8.24	0.66
10- 20	37.5	7.30	8.09	0.52	1.07	1.38	2.17		2.47	4.92	-	2.28	0.30	0.19	2.50	5.27	0.36
20- 30	36.8	7.90	8.34	0.50	0.93	1.25	2.36		2.81	5.01	-	2.70	0.30	0.38	2.00	5.38	1.83
30- 40	39.1	8.02	8.40	0.44	1.03	1.37	1.57		1.84	4.29	-	2.66	0.15	0.53	1.00	4.34	6.56
40- 50	39.3	8.16	8.61	0.53	1.19	1.88			1.07	4.14	-	2.94	0.43	0.48	0.50	4.35	8.80
50- 60	43.1	8.22	8.79	0.70	4.00	2.39			0.24	6.63	-	4.50	0.52	0.92	0.75	6.69	10.27
60- 70	38.4	8.37	8.92	1.06	7.52	3.10			0.49	11.11	-	8.16	0.35	1.50	1.00	11.01	15.79
70- 80	34.4	8.73	9.15	1.68	13.91	3.68			-[1]	17.59	-	13.11	0.76	2.79	0.50	17.16	20.32
80- 90	34.1	9.39	9.57	3.00	27.39	4.94			-	32.33	4.50	19.16	2.77	4.42	0.25	31.10	20.96
90-100	32.6	9.62	9.75	4.60	45.22	5.65			-	50.87	11.07	20.96	10.07	7.50	-	48.60	17.18
100-110	37.6	9.93	10.00	8.10	82.61	7.30			-	89.91	25.73	23.51	24.56	14.42	-	58.22	12.84
110-120	40.0	10.06	10.09	10.80	113.22	8.34			-	121.56	38.25	27.32	36.34	20.10	-	122.01	12.10

[1] not further checked (pH > 9)

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Profiles nrs.28 A & B (NaNo-A, NaNo-B)

GENERAL DATA

Area: Girtasho
Location: 10 km NNW of Naabi Hill, along the main road;
A and B profiles located 5 m apart, at NaNa site
Coördinates: 9695.75 N, 718 E (1:250.000 Serengeti Map)
Altitude: 1655 m
Described by: H.A.de Wit
Date: 7/8-12-1971
Climate: prolonged dry season; bright
Aerial photo: Serengeti 1972, L 11-S, 3-101 (Finn Map)
Physiography: top of very gently sloping ridge
Topography: flat or concave relief
Slope: level
Erosion: none
Parent material: (silty) clayey aeolian deposit, volcanic origin
Landuse: National Park; extensive grazing in the past by Masaai cattle
Natural vegetation 1): Spot A: Agre 9, Cyda 1, Pest 1, Miku 1, Sfim 2, Erte 1, Hars +, Solincan 1; total cover 70-80%
Spot B: Dima 5, Pest 2, Miku 3, Sfim 3, Erte 1, Erci 1, Cyda 2, Hars 1, Arke 1, Agre 1, Eupa 1, Cpic 1, Sidovata 1, Becium sp.+; basal cover 20%, total cover 40%
At both spots the grasses are withered at the time of description, except for Sfim and Cyda; vegetation strongly grazed
Drainage condition: well drained
Groundwater depth: -
Permeability: NaNo-A: moderate at the surface and at lower depth (35 cm)
NaNo-B: moderate at the surface, moderately rapid at lower depth (27.5 cm)
Moisture: A and B: dry 0-50 cm, slightly moist to moist below 50 cm
Stoniness: Class 0
Salinity: Spot A: 0-120 cm non-saline, below 120 cm slightly saline
Spot B: 0-40 cm non-saline, 40-50 cm moderately saline, below 50 cm strongly saline
Root distribution: Spot A: main mass 0-50 cm, common fine roots; few fine roots below 70 cm
Spot B: main mass 0-40 cm, common fine roots; 40-120 cm fine roots become gradually less common
Biological activity: Spot A: many small earth piles, up to 30 cm diameter, of fine and medium angular blocky material cover the soil surface; few holes (krotovina like), a single dungbeetle ball, many spherical clayey elements in top soil; termites between 0-25 cm
Spot B: few medium sized dung pockets 0-50 cm, common darkbrown ants and nests in upper horizons of both the A and B profile
Human activity: extensive grazing in the past
Spot A: potsherds found at a depth of about 20 cm

Remark: profiles were dug on 12-10-1971; the walls of the pit were dry.

1) for abbreviations of species names and explanation of cover values, see Appendix 47 and Part I, Ch 2: Methods.

PROFILE DESCRIPTION NaNo-A

A 1.1 0-5 cm; 10 YR 4/2 when dry, 10 YR 2/1 when moist silty clay loam; moderately strong medium subangular blocky, porous elements (clods), often attached to roots; (slightly) hard when dry, (very) friable when moist, slightly sticky and slightly plastic when wet; many micropores, common meso biopores; common fine, few medium roots; lower boundary clear and wavy.

A 1.1 (cont.) 5-24 cm; 10 YR 4,5/2 when dry, 10 YR 2,5/1,5 when moist silty clay loam; moderately strong very coarse compound prismatic which can be subdivided into moderate medium and coarse porous subangular blocky elements, falling apart into moderately strong fine and medium (sub)angular blocky when disturbed; slightly hard when dry, very friable when moist, slightly sticky and slightly plastic when wet; many micro, common meso and few large biopores; common fine, few medium roots; common fine spherical, peeling clayey elements, very hard when dry (cores of old dungbeetle balls?); many very fine crumbs, excrement-like (worms!),often weakly cemented to larger elements, especially occurring between the major structural elements; cracks between the major structural elements up to 5mm; lower boundary clear, locally abrupt and slightly wavy.

A 1.2 24-45 cm; 10 YR 5/1,5 when dry (rubbed), 10 YR 3/1,5 when dry(broken), 10 YR 2/1 when moist, silty clay; moderate coarse and very coarse compound prismatic but locally columnar structure, the elements form usually one unit with the prisms of the overlying horizon because of cracking; they fall apart into moderately strong medium and coarse angular blocky elements, hard when dry, firm when moist, (very) plastic and very sticky when wet; common micro, common fine, few meso biopores; common fine, few medium roots, also common fine old roots within the structural elements; many distinct coatings on the faces of the smaller structural elements, 10 YR 3/1,5 when dry; common very fine crumbs (excrements); cracks up to 10 mm wide, narrowing near upper and lower boundary; lower boundary clear and slightly wavy.

A 1.3 ca 45-70 cm; 10 YR 5/3 when dry, 10 YR 3/3 when moist, calcareous silty clay above, loam near lower boundary; weak very coarse prismatic near upper boundary, falling apart into moderate coarse angular blocky elements when disturbed, almost structureless, massive below; soft when dry, very friable when moist, slightly sticky and slightly plastic when wet; many micro, common macropores, spongeaous porosity; common to few fine roots; lower boundary clear and smooth.

C ca 70-120 cm; 10 YR 6/3 when dry, 10 YR 4/3 when moist, calcareous loam; structureless, single grain; loose when dry, almost loose when moist; non-sticky and almost non-plastic when wet; few fine roots; many fine to coarse weakly cemented elements, hard when dry, becoming abundant downwards, below 90 cm succeeded by (very) hard, often very irregularly shaped lime concretions with colours being the same as those of the soil material; lower boundary gradual and smooth.

C 2 ca 120-150 cm (bottom of pit); 10 YR 6/3,5 when dry, 10 YR 4,5/4 when moist loam; structureless, slightly massive, locally stratified; soft when dry, very friable when moist, non-sticky and slightly plastic when wet; many micro- and mesopores, spongeous porosity;

very few fine roots; common medium weakly cemented elements with fine whole veins and medium irregularly shaped (very) hard concretions, decreasing in number downwards; soil material tastes slightly saline.

Remarks:-in the 45-70 cm layer a gradual boundary at 57 cm may be taken into consideration.
-below 180 cm the soil was difficult to penetrate by soil auger (pan).

Classification according to Soil Taxonomy (1975)

Diagnostic surface horizon: Mollic epipedon
Diagnostic subsurface horizons: Cambic horizon
Calcic horizon (90-120 cm)
Other diagnostic characteristics: Exchange complex dominated by amorphous materials.
Soil moisture regime: Ustic
Soil temperature regime: Isothermic

Order: Mollisols
Suborder: Ustolls
Great Group: Haplustoll
Subgroup: Typic Haplustoll
Family: Fine, mixed over thixotropic (calcareous), isothermic

PROFILE DESCRIPTION NaNo-B

A 1.1 0-20 cm; 10 YR 5/2 when dry (rubbed), 10 YR 4,5/2 when dry (broken), 10 YR 3/1 when moist silty clay loam; weak coarse subangular blocky, which falls easily apart into moderately strong fine and medium subangular blocky porous elements above, and moderate fine and medium crumbs near the lower boundary; slightly hard when dry, very friable when moist, non-sticky and slightly plastic when wet; common micro, common meso and few large biopores; common fine roots; common fine and medium spherical clayey elements (cores of old dungbeetle balls?), very hard when dry; a few narrow vertical cracks were recorded; lower boundary clear and smooth.

A 1.2 20-40 cm; 10 YR 4/2 when dry, 10 YR 3/1,5 when moist silty clay; weak coarse subangular blocky, easily falling apart into single grains and very fine crumbs, structure, however, becomes more distinct near lower boundary; soft when dry, very friable when moist, non-sticky and slightly plastic when wet; many micro, common meso pores; common fine roots; common fine spherical clayey elements (dunbeetle balls), very hard when dry; few narrow cracks near the lower boundary; lower boundary clear and wavy.

A 1.3 ca,sa 40-60 cm; 10 YR 5/2 when dry (rubbed), 10 YR 4/2 when dry, 10 YR 2,5/1,5 when moist calcareous silty clayloam; moderately weak very coarse prismatic; slightly hard or hard when dry, very friable when moist,slightly sticky and slightly plastic when wet; many micro, common mesopores, spongeous porosity; common fine roots, but less common than in the overlying horizon; few narrow cracks between the prisms, few horizontal cracks near the lower boundary; soil material tastes strongly saline-alkaline (soda) near the lower boundary; lower boundary gradual and smooth.

C ca,sa 60-80 cm; 10 YR 5/3 when dry, 10 YR 3/3 when moist, silt loam; structureless, massive, but tending to single grain near lower boundary; slightly hard when dry, very friable when moist, slightly sticky and slightly plastic when wet; many micro, common meso pores, spongeous porosity; (few to) common fine roots; fine and medium weakly cemented clods, often irregularly shaped, 10 YR 7/4 when dry, 5/4 when moist, hard when dry, becoming gradually more common towards the lower boundary; few medium worm-casts; soil material tastes strongly saline-alkaline (soda); lower boundary clear and smooth.

C 2 ca,sa 80-140 cm (bottom of pit); 10 YR 6/4 when dry, 10 YR 4/4 when moist sandy loam; structureless, single grain when dry, slightly massive when moist; loose when dry and slightly massive when moist, non-sticky and non-plastic when wet;common meso and large old biopores; few (to common) fine roots, very few between 120 and 140 cm; abundant medium to very coarse weakly cemented clods, forming an almost continuous "soft" pan below 120 cm, 10 YR 4/4 when dry, 10 YR 3,5/4 when moist inside, hard to very hard when dry, very firm when moist, with common fine white veins inside (old root channels ?); the soil material tastes strongly saline-alkaline (soda).

Classification according to Soil Taxonomy (1975)

Diagnostic surface horizon:	Mollic epipedon
Diagnostic subsurface horizons:	-Cambic horizon -Calcic horizon (90-120 cm)
Other diagnostic characteristics:	Exchange complex dominated by amorphous materials
Soil moisture regime:	Ustic
Soil temperature regime:	Isothermic
Order:	Mollisols
Suborder:	Ustolls
Great Group:	Haplustoll
Subgroup:	Typic Haplustoll (saline phase)
Family:	Fine, mixed over thixotropic (calcareous) isothermic.

Profile no.47 (NaNo-S)

GENERAL DATA

Area: Girtasho
Location: about 7.5 km NW of Naabi Hill, 1.75 km W of main road
Coördinates: 9693 N, 718 E (1:250,000 Serengeti Map)
Elevation: 1645 m
Described by: H.A. de Wit
Date: 31-8-1973
Weather condition: bright, almost no rain for last 2 months
Aerial photo: Serengeti 1972, L 11-S, 3-101/102 (Finn Map)
Physiography: valley bottom
Topography: flat or concave
Slope: -
Erosion: none
Parent material: clayey deposit of volcanic ash
Landuse: National Park
Vegetation 1): Cyda 3, Eupa 3, Dima 3, Pest 2, Cpic 2, Peme 2, Agre 1, Erte 1, Erci 1, Arke 1, Ttri 1, Patr 1, Sfim 2, Panicum sp +; Indbasif 2, Justelli 2, Solincan 1, Sidovata 1 (green), Euphinae +;
Eupa, Cyda, Sfim, Pest and locally also Dima have green base and sometimes a few short green leaves; Indbasif and Justelli (flowering) give the vegetation a characteristic appearance as both herbs cover the soil for about 50%; total soil cover almost 100%
Drainage condition: well drained at date of description, in wet season probably somewhat poorly drained
Groundwater depth: not been established, groundwater very deep or absent
Permeability: surface: moderate; 13-40 cm: very rapid but locally moderately slow; below 40 cm: slow
Moisture: moist throughout, varying between 24 (surface) and 27 (bottom) weight %
Stoniness: no stones or gravel
Salinity: non-saline throughout
Root distribution: 0-130 cm (bottom of pit), main mass 0-40 cm
Biological activity: 3 globular inhabitedtermite nests up to 10 cm diameter with plastered walls, within a depth of 50 cm; small dungbeetle balls within 40 cm common; in the field big dungbeetle balls up to 3 inches were found

1) for abbreviations of species names and for explanation of cover values see Appendix 47 and Part I, Ch 2: Methods

PROFILE DESCRIPTION

A 1.1 0-13 cm; 10 YR 4/1.5 when dry, 10 YR 3/1 when moist, 2/1 when wet, silty clay; moderately weak compound very coarse blocky structure, falling apart into strong very fine and fine (sub)angular blocky when drying out, often attached to roots, with a medium and thick platy surface crust, locally some coarse blocky elements just below the surface; hard when dry, friable when moist, sticky and plastic when wet; few large, common meso biopores, common fine biopores, many micropores (in and between the very fine aggregates); few large and medium roots, common to many fine roots; few fine holes with plastered walls; common larvae; many fine cracks between the fine aggregates; lower boundary clear and slightly wavy.

A 1.2 13-40 cm; 10 YR 3/1 when dry, 10 YR 2/1 when moist, clay; moderate coarse and very coarse prismatic falling apart into strong (above, to moderate (below) medium to very fine angular blocky (almost granular) aggregates; hard when dry, firm when moist, plastic and sticky when wet; few large, common fine, few to common meso biopores, many(?) micropores; few large and medium roots, common fine roots, becoming less common towards lower boundary; common recent medium dungbeetle balls with brown walls peeling off; few cracks up to 5 mm wide near lower boundary; common darker coloured coatings on aggregate surfaces; lower boundary gradual and smooth.

A 1.3 40-90 cm; 10 YR 2-2.5/1 when dry, 10 YR 2/1 when wet clay; (moderately) strong coarse and very coarse prismatic, rather massive, which can be broken into coarse prismatic and sharply edged angular clods with much very fine blocky above and little very fine blocky and granular material below; very hard when dry, very firm when moist, very sticky and very plastic when wet, especially below; few meso, few to common (above) fine biopores, common(?) micropores; few medium roots, common (above) to few (below) fine roots, often along the surfaces of the structural elements; common darker coloured coatings, especially on faces of smaller aggregates; locally pockets in which very fine sandgrains are common; a single krotovina-like element, running vertically, more brownish than the surrounding material (10 YR 3-3.5/2 when dry) about 3 inches in diameter was found; few fine rounded lime concretions at 67 cm; between the structural elements cracks up to 15 mm wide were recorded; lower boundary gradual and wavy.

A 1.4 90-114 cm; 10 YR 3/1-2 when dry, 10 YR 2/1-2 when moist clay; moderately strong very coarse prismatic which can be broken into sharply edged coarse and very coarse angular elements; very hard when dry, very firm when moist, very sticky and very plastic when wet; few meso and fine biopores, common(?) micropores; few medium and few fine roots; common medium and coarse slickensides (intersecting); locally common fine sandgrains; few fine powdery lime veins and pockets; common lighter coloured parts (mottles?), 10 YR 3/2 when dry; few above, below common fine and medium rounded lime concretions, 10 YR 7/2 when dry, indurated; lower boundary clear, almost abrupt and smooth.

C 114-130 cm (bottom of pit); 10 YR 5/2.5-3 when dry, 10 YR 3.5-2.5 when moist calcareous silty clayloam; almost structureless; firm when moist above, more loose below, sticky and plastic when wet; many (above) to abundant indurated lime concretions, fine and medium above, rather rounded, medium and coarse, irregularly shaped below with sandgrains included; concretions form over 50% of the volume.

Remark: The very fine aggregates in the 0-13 and 13-40 horizons proved to be very stable during infiltration experiments, whereas the hard prisms at lower depth tended to turn into soft mud (much swelling too) when wetted.
The 40-90 cm horizon might be subdivided into an upper (40-70 cm) and a lower part (70-90 cm)

Classification profile 47 according to Soil Taxonomy (1975):

Diagnostic surface horizon: Mollic epipedon
Diagnostic subsurface horizon: Cambic horizon
Other diagnostic characteristics:
- clay contents 50-60% (0-110 cm)
- coarse slickensides between 90-114 cm
- cracks over 10 mm wide at 50 cm, extending from 0-90 cm
- exchange complex dominated by amorphous materials

Soil moisture regime: Ustic
Soil temperature regime: Isothermic
Order: Vertisols
Suborder: Usterts
Great Group: Pellusterts
Subgroup: Typic Pellustert
Family: Fine, mixed over thixotropie, isothermic

Profile Nr.46 (NaLag)

GENERAL DATA

Area: Olduvai
Location: 6.25 km SSW of Naabi Hill
Coördinates: 9680 N; 720 E
Elevation: 1650 m
Described by: H.A.de Wit
Date: 16-8-1973
Weather condition: bright, almost no rain during 2 moths, possibly one shower few days before description
Aerial photo: Serengeti 1972, 3-28/29 L 12-N (Finn Map)
Physiography: flat plain, aeolian deposits of volcanic ash
Topography: flat
Slope: none
Erosion: none
Parent material: (silty)clay
Landuse: National Park for over 10 years
Vegetation 1) : Andropogon greenwayi grassland with much Chloris picnotrix: Agre 8, Cpic 3, Dima 1, Cyda 1 (green), Eupa 1, Sfim 1, Pest 1, Erte 1, Hars +, Patr +, Helisteu 1, Solincan 1, Justexig 1 (three latter herbs green), Crotspin 1, Euphinae +, Kyllnerv +, Enicohys +; Heliotropium steudneri is the dominant herb (in flower), often occurring in patches with much Cpic, alternating with more pure stands of Agre, total cover 90-100 %, elsewhere sometimes 70-90 %
Drainage condition: well drained
Groundwater depth: could not be established
Permeability: surface: moderate-moderately slow
7.5 cm: moderate
32.5 cm: moderately rapid
Moisture: dry 0-10 cm, moist below 20 cm, over 20% by weight
Salinity: non-saline 0-150 cm
Root distribution: 0-160 cm(bottom of pit), main mass 0-20 cm
Biological activity: beetles and larvae common in 0-20 cm layer, also ants, one termite nest at 100 cm, few old dungbeetle balls at about 60 cm
Human activity: Extensive cattle ranching by Masai
Remark: common vertical cracks up to 15 mm wide (above) between the surface 0-10 cm and 55 cn depth

1) for abbreviations of species names and explanation of cover values, see Appendix 47 and Part I Ch.2: Methods.

PROFILE DESCRIPTION

A 1.1 0-20 cm; 10 YR 3.5/1-1.5 when dry, 10 YR 2/1 when moist silty clay; moderate very coarse blocky and coarse prismatic, which can be subdivided (when dry) into strong fine and medium blocky elements, especially near the surface, often attached to roots; more unaggregated material between 10 cm andlower boundary; very hard when dry, firm to very firm when moist, sticky and plastic when wet; few large, common meso and fine biopores, common? micropores; common fine, few -but locally common- medium, few large roots (herbs); common fine and medium globular clayey elements (dungbeetle balls) very hard when dry; few fine excrements (worms?); common larvae in medium sized holes with weakly cemented walls; few vertical cracks 15 to 30 cm apart, up to 15 mm wide; lower boundary clear and wavy.

A 1.2 20-55 cm; 10 YR 3/2 when dry, 10 YR 2/1.5-2 when moist clay; moderate coarse prismatic falling apart into very coarse and coarse angular blocky elements, moderate above, weaker below; hard when dry, firm when moist, sticky and plastic when wet; few large and meso, common fine biopores, common(?) micropores; few medium and common fine roots; common fine and medium blobular clayey elements (with peeling walls); few darker coloured coatings (clay-skins?); lower boundary gradual and wavy.

C ca 55-75 cm; 10 YR 4.5/2 when dry, 10 YR 3/2 when moist calcareous silt loam; almost structureless, massive, falling apart into moderate medium and coarse subangular clods when disturbed; slightly hard when dry, friable when moist, slightly sticky and slightly plastic when wet; locally hard when dry and firm when moist; few meso, common fine biopores, many micropores; few, locally common fine roots, few medium roots; common fine and medium mottles, 10 YR 4/2 when dry; few very fine white veins; lower boundary clear and slightly wavy.

C 2 ca 75-95 cm; 10 YR 5/2-2.5 when dry, 10 YR 3.5/2-2.5 when moist calcareous loam; almost structureless, for the greater part falling apart into very fine crumb and single grain when disturbed; soft to slightly hard when dry, very friable when moist, non to slightly sticky and slightly plastic when wet; many micropores; few fine and medium roots; common fine and medium darker coloured clayey elements 10 YR 3/2 when dry; common weakly cemented clods; many fine and medium white lime pockets and veins; lower boundary gradual and wavy.

C 3 ca 95-110 cm; 10 YR 5/2.5 when dry, 10 YR 4/2.5 when moist, alternating with 10 YR 5/4-5 when dry, 10 YR 3.5/4 when moist, calcareous loam; almost structureless, falling apart into weak fine and medium subangular clods; soft when dry, very friable when moist, almost non-sticky and slightly plastic when wet; many micropores; few meso common fine biopores; few fine roots; common medium, irregularly shaped concretions, strongly cemented but breakable; many fine and medium weakly cemented clods, mostly yellowish brown, especially common near lower boundary; lower boundary clear and wavy, locally irregular.

C 3 ca 110-160 cm; calcareous sandy loam; brittle mass of coarse and very coarse strongly cemented sometimes indurated, irregularly shaped concretions, hardly or not breakable by hand, in a matrix of single grain (when dry) and weakly cemented very fine and fine aggregates; few fine roots (seem to be more common than in overlying horizon).

Classification according to Soil Taxonomy (1975) :

Diagnostic surface horizon:	Mollic epipedon
Diagnostic subsurface horizon:	Cambic horizon
Other diagnostic characteristics:	Exchange complex dominated by amorphous materials
Soil moisture regime	Ustic
Soil temperature regime	Isothermic
Order	Mollisols
Suborder	Ustolls
Great Group	Haplustoll
Subgroup	Typic Haplustoll
Family	Fine mixed over thixotropic, isothermic

Textural data, organic carbon and lime contents, P (citric acid) and N (total soil) for soils of Soil landscape 1.1 and 1.2, according to Oosterbeek methods (see Part I, Ch.2: Methods)

	% of total soil		% of total mineral fraction										
Profile, depths	org.C	$CaCO_3$	<2 µm	2-16µm	16-50µm	50-105µm	105-150µm	150-210µm	210-300µm	>300µm	P	N
BARSEK												
12.5-25	8.4	7.9	14.3	16.2	32.4	13.3	11.7	8.1	2.4	1.7	3.0	0.20
45 -60	5.4	15.5	11.2	17.1	15.1	13.8	12.2	10.4	5.8	14.4		
SEK-NE												
0-16	9.0	0.4	29.6	29.7	24.8	8.1	5.0	1.7	0.5	0.6		0.37
30-40	6.6	0.8	30.7	32.8	17.9	9.4	6.0	1.9	0.6	0.7		
55-70	6.6	2.9	29.9	35.3	19.4	7.9	4.5	1.6	0.6	0.8	0.18	
90-110	5.3	3.3	31.9	41.6	14.9	5.9	3.1	1.3	0.5	0.8		
130-150	4.4	4.1	29.8	40.2	15.8	6.6	3.5	1.8	0.8	1.4		
190-210	3.5	2.4	17.6	21.3	12.1	8.4	6.5	5.5	4.8	23.8		
NaNo-A												
0-25	7.4	0.3	37.8	27.7	19.4	6.8	3.9	1.3	0.7	2.4	338	0.31
25-45	3.9	0.3	40.1	24.5	20.2	7.2	3.8	1.4	0.7	2.1		
45-57.5	3.2	0.1	41.8	22.3	21.3	6.6	4.0	1.5	0.6	1.9		
70-95	4.7	20.4	10.8	19.8	15.2	13.1	9.0	5.8	4.3	22.0		
120-140	4.0	10.2	10.1	23.2	20.2	13.6	9.2	6.4	4.0	13.3		
0-25[2])	-	0.4	42.3	27.3	17.0	6.1	4.3	3.1				
NaNo-B												
0-20	6.3	0.3	34.1	29.0	21.5	7.6	4.1	1.3	0.6	2.0		0.27
20-40	3.9	0.3	41.0	26.5	18.0	6.7	4.0	1.3	0.7	1.8		
50-60	4.4	2.0	33.7	33.7	17.7	7.0	4.1	1.4	0.7	1.9		
80-100	6.7	17.8	14.3	45.4	17.0	10.6	5.8	2.4	1.3	3.2		
120-140	5.1	15.2	6.5	19.2	14.0	12.2	9.0	6.5	5.0	27.6		
80-100[2])	-	22.1	23.6	35.4	29.2	5.4	4.0		2.5			
NaNo-S												
0-13	8.3	0.3	50.0	29.5	13.1	3.0	1.6	0.7	0.5	1.6		0.36
26-40	4.5	0.4	62.9	25.7	5.5	2.4	1.3	0.6	0.3	1.3		
55-70	2.2	0.3	63.1	19.5	10.4	2.4	1.5	0.8	0.6	1.7		
90-114	2.2	0.4	59.2	24.0	9.3	2.8	1.4	0.8	0.7	1.8		
114-130	3.3	10.6	30.7	34.6	14.8	3.3	2.9	2.2	1.6	9.9		
Na-Lag												
0-20	5.3	0.2	49.7	25.3	15.4	5.9	2.4	0.5	0.2	0.6		0.23
20-37.5	3.2	0.2	54.4	22.1	14.7	5.1	2.3	0.6	0.2	0.6		
55-75	5.5	1.4	19.5	42.6	20.2	5.0	3.6	1.6	0.7	6.8		
95-110	4.6	4.3	12.5	22.9	12.7	7.3	5.0	3.8	3.0	32.8		
130-150	4.5	7.9	6.6	14.5	6.3	5.5	4.2	3.4	4.0	55.5		

1) by loss on ignition.

2) samples pretreated with Na-EDTA to dissolve $CaCO_3$ (in stead of 1 N HCl)

Soil Landscape I.2 (Andropogon greenwayi grasslands): mean infiltration rates (mm/h)

profile, depths (cm)	Exp.[1]	n[2]	mean infiltr. rate	lowest value	highest value	mm infiltr. (averages)
NaNo-A						
Surface	I	15	531.0	74.6	1491.6	12.43
	II	15	67.0	11.3	198.9	12.43
	III	15^{*}	52.7	10.8	248.6	12.43
	IV	15^{**}	35.6	10.8	139.8	12.43
32.5/35 cm	I	5	1139.5	39.8	4474.8	12.43
	II	5	103.1	6.7	298.3	12.43
	III	5^{*}	36.4	6.7	82.1	12.43
	IV	5^{**}	22.4	6.7	67.8	12.43
NaNo-B						
Surface	I	13	58.0	25.3	144.4	12.43
	II	13	26.1	13.8	46.4	12.43
	III	13	26.0	14.6	45.4	12.43
27.5 cm	I	5	291.3	198.9	497.2	12.43
	II	5	85.1	53.6	119.3	12.43
	III	5	77.6	45.7	96.2	12.43
	IV	5	70.2	43.2	90.4	12.43
	V	5	65.4	42.0	90.4	12.43
	VI	5	64.4	40.7	92.3	12.43
NaNo-S						
Surface	I	10	1013.7	120.3	4474.8	14.30
	II	10	69.3	10.9	157.0	14.30
	III	10	32.5	8.1	53.3	12.28
	IV	10^{*}	30.4	$\leqslant$ 8.1	48.6	10.88
	V	10^{**}	28.9	" 8.1	43.9	10.56
	VI	10^{**}	29.5	" 8.1	44.7	10.88

profile depths (cm)	Exp.[1]	n[2]	mean infiltr. rate	lowest value	highest value	mm infiltr. (averages)
NaNo-S (cont.)						
27.5 cm	I	6	5600.0	34.2	11188.0	15.54
	II	6	1028.9	12.7	2237.8	15.54
	III	6^{*}	656.7	$\leqslant$ 12.7	1598.4	15.02
	IV	6^{*}	546.8	" 12.7	1243.2	15.02
	V	6^{**}	476.5	" 12.7	1118.9	15.02
	VI	6^{**}	405.7	" 12.7	799.2	15.02
	VII	6^{**}	356.5	" 12.7	745.9	15.02
	VIII	6^{**}	333.1	" 12.7	699.3	15.02
	IX	6^{**}	312.5	" 12.7	699.3	15.02
	X	6^{**}	320.7	" 12.7	745.9	15.02
52.5 cm	I	4	4.7	2.2	10.3	9.71
Na-Lag						
Surface	I	10	401.1	25.2	1864.8	15.54
	II	10	79.2	4.1	399.6	15.23
	III	10^{**}	40.2	$\leqslant$ 4.1	294.4	14.51
7.5 cm	I	7	1608.3	39.4	8949.6	15.10
	II	7	244.9	7.7	1431.4	14.30
	III	7^{*}	45.6	$\leqslant$ 7.7	140.3	12.07
	IV	7^{*}	37.8	" 7.7	99.4	12.07
	V	7^{*}	36.3	" 7.7	99.4	11.99
32.5 cm	I	6	269.6	21.7	621.6	15.54
	II	6	91.8	11.1	207.2	15.02
	III	6^{*}	80.2	$\leqslant$ 11.1	169.5	14.50
	IV	6^{**}	73.7	" 11.1	154.3	13.99
	V	6^{**}	72.4	" 11.1	147.2	13.99

1) Number of infiltration experiment

2) Number of rings used

* one figure lacking; infiltration experiment stopped for 1 ring; last known value filled (assumed to have become constant -not always true!)

** ditto, but 2 or more figures lacking; never exceeding 33% of total number (N)

Appendix 23

Golzu I - A (<u>Andropogon</u> <u>greenwayi</u> spot)

depth (cm)	SP	pH_p	pH_e	EC_e	Na^+	K^+	Ca^{2+}	$Ca^{2+} + Mg^{2+}$	Sum +	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Sum -	% Lime
								all in meq/l of the sat. extracts								
0- 10	55.9	7.15	8.10	0.45	0.86	1.26	1.95	2.43	4.55	-	3.25	0.27	-	0.75	4.27	0.04
10- 20	51.9	7.36	8.00	0.32	0.96	0.84	1.13	1.45	3.25	-	1.84	0.56	-	0.75	3.15	0.20
20- 30	49.2	7.50	7.87	0.42	1.18	0.99	1.59	1.91	4.08	-	2.12	0.46	-	1.25	3.83	0.12
30- 40	47.3	7.69	8.27	0.38	1.04	0.94	1.32	1.55	3.53	-	2.61	0.60	-	0.50	3.71	0.72
40- 50	45.2	7.77	8.46	0.47	1.89	1.18	1.32	1.78	4.85	-	2.97	0.40	-	1.00	4.37	6.04
50- 60	42.4	7.93	8.66	0.55	3.93	1.16	0.66	1.05	6.14	-	4.77	0.89	-	0.25	5.91	6.51
60- 70	42.8	8.10	8.69	0.75	6.57	1.09	-	0.23	7.89	-1)	6.92	0.53	0.10	0.10	7.65	5.62
70- 80	41.1	8.21	8.89	1.01	10.13	1.38	-	0.26	11.77	-1)	9.75	1.49	-	-	11.24	5.42
80- 90	38.9	8.42	-	1.38	15.74	1.83	-	0.20	17.77	-1)	12.51	0.96	3.00	-	16.47	7.87
90-100	41.3	8.81	9.26	1.97	20.52	2.06	-	0.20	22.78	-1)	17.24	1.40	4.80	-	23.44	12.46

Golzu I - B (<u>Digitaria</u> <u>macroblephara</u> spot)

depth (cm)	SP	pH_p	pH_e	EC_e	Na^+	K^+	Ca^{2+}	$Ca^{2+} + Mg^{2+}$	Sum +	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Sum -	% Lime
0- 10	44.2	7.39	8.33	0.51	1.57	1.30	2.25	2.89	5.76	-	4.95	0.37	0.20	-	5.52	0.17
10- 20	41.8	7.68	8.45	0.53	2.35	1.18	1.85	2.27	5.80	-	3.60	0.23	0.43	1.50	5.76	0.22
20- 30	38.2	7.96	8.70	0.60	4.78	1.00	0.93	1.05	6.83	-1)	4.59	0.73	1.00	0.75	7.07	0.18
30- 40	39.2	8.23	8.66	1.80	17.13	1.24	-	0.99	19.36	-1)	6.08	8.67	3.98	-	18.73	3.25
40- 50	45.0	9.16	9.33	4.28	46.96	1.76	-	0.23	48.95	-1)	24.38	13.68	12.83	-	50.29	4.08
50- 60	46.1	9.98	10.07	16.00	219.13	6.11	-	0.13	225.37	111.09	82.15	12.48	31.09	-	236.81	5.67
60- 70	46.3	10.28	10.36	21.00	288.70	6.98	-	0.13	295.81	188.26	79.71	11.78	26.35	-	306.10	5.98
70- 80	42.2	10.33	10.40	25.40	393.05	9.03	-	0.13	402.21	248.46	92.01	11.53	33.16	-	385.16	10.67
80- 90	42.5	9.99	10.08	26.60	400.00	10.44	-	0.13	410.57	234.90	132.92	9.77	32.76	-	410.35	10.54
90-100	42.0	9.94	10.02	24.90	366.96	10.19	-	0.13	377.28	204.37	133.56	9.16	30.99	0.25	378.33	18.78

1) No carbonate ions were found in extracts with pH <8.5 because the water, used for diluting, was fairly acid (pH <5)

Appendix 28

profile, depth(cm)	SP	pH_p	pH_e	EC_e	Na^+	K^+	$Ca+Mg^{2+}$	Sum +	$HCO_3^-+CO_3^{2-}$	NO_3^-	% Lime
					all concentrations in meq/1 of the sat. extract						
Hivak-SW[1] - A											
0- 20	61.4	6.15	7.84	0.50	0.89	1.44	2.50	4.83	1.53	-	0.06
20- 40	65.7	6.21	7.70	0.28	0.68	0.81	1.08	2.57	1.05	-	0.04
40- 60	65.4	6.45	7.79	0.29	1.18	0.75	0.88	2.81	0.87	-	0.20
60- 80	60.5	6.87	8.19	0.36	1.91	0.77	0.88	3.56	1.46	-	0.19
80-100	58.0	7.38	8.68	0.77	4.78	1.12	1.62	7.52	4.25	0.50	0.56
100-120	53.7	7.61	8.70	0.97	6.87	1.20	1.55	9.62	5.26	0.50	0.84
Hivak-SW[1] - B											
0- 20	55.0	6.19	7.94	0.46	0.89	1.29	2.03	4.21	1.36	-	0.12
20- 40	59.4	6.60	8.09	0.35	1.37	0.76	1.28	3.41	1.36	-	0.19
40- 60	58.4	7.01	8.18	0.43	2.93	0.49	0.81	4.23	2.18	-	0.25
60- 80	55.4	7.36	8.67	1.20	10.30	0.81	0.81	11.92	5.61	-	0.40
80-100	54.4	7.59	8.50	0.82	7.17	0.56	0.95	8.68	3.54	-	0.09
100-120	54.9	7.72	8.54	1.16	10.15	0.70	1.28	12.13	5.10	-	1.33
Old. Olobaie - A											
0- 20	63.2	6.25	7.92	0.43	0.77	1.80	1.59	4.16			0.32
20- 40	59.2	6.27	7.76	0.44	0.94	1.73	1.35	4.02			0.20
40- 60	67.6	6.47	8.01	0.40	1.09	1.86	0.94	3.89			0.25
60- 80	62.2	7.10	8.51	0.65	2.02	3.18	1.38	6.58			0.53
80-100	54.8	7.84	8.95	0.92	4.66	4.03	0.88	9.57			2.17
100-120	50.6	8.10	8.93	1.26	7.74	4.07	0.54	12.35			2.16
Old. Olobaie - B											
0- 20	55.0	6.24	7.99	0.38	0.75	1.52	1.45	3.72			0.06
20- 40	52.3	6.59	8.13	0.41	1.23	1.61	1.15	3.99			0.25
40- 60	52.9	6.84	8.35	0.51	2.03	2.07	0.91	5.01			0.05
60- 80	50.2	7.33	8.64	0.76	3.23	2.88	0.94	7.05			0.48
80-100	50.4	7.90	8.74	1.28	6.30	4.57	1.08	11.95			0.78
100-120	50.9	8.10	8.60	2.70	15.61	7.67	1.61	24.89			1.30

[1] Hivak-SW : Hidden Valley kopjes-South-West
(A)-Spots: Andropogon greenwayi dominant grass species
(B)-Spots: Andropogon greenwayi absent, various combinations of other grass-species

Profile Nr.13 (G.T.III-Girtasho ridge top)

GENERAL DATA

Area: Girtasho
Location: about 27 km SSW of Seronera, Serengeti National Park
Coördinates: 9705.5 N, 714 E (1-250,000 Serengeti Map)
Altitude: 1670 m
Described by: H.A. de Wit
Date : 28-11 and 5-12 1970
Weather condition: beginning of wet season; rain during 10 days before
Aerial photo: Serengeti 1972, 3-99, L 11-S (Finn Map)
Physiography: top of gently sloping hill
Topography: subnormal relief (locally: flat or concave)
Slope: A-class; level
Erosion: none
Parent material: silty aeolian deposit
Landuse: National Park; grazing by game animals; grazing by Masai cattle in the past
Vegetation 1): burned 1½ month ago; vegetation recovering rapidly after the onset of the rains; long grassland, fairly short physiognomy; Dima 6, Cyda 4, Miku 3, Disc 2, Peme 1, Pest 1; basal cover of about 30%, total cover 50%
Drainage condition: well drained
Groundwater depth: absent
Permeability: moderate in the surface soil, moderately rapid at lower depth (25-30 cm)
Moisture: moist below 60 cm, increase of moisture content downwards (Nov.28th); moist throughout the profile (Dec.5th)
Stoniness: class 0; few "boma" stones on the surface in the neighbourhood.
Salinity: non-saline 0-50 cm; slightly saline 50-60 cm; moderately saline below 60 cm
Root distribution: 0-100 cm (bottom of pit); main mass 0-30(-60)cm
Biological activity: few large biopores in 0-10 cm layer (ant or spider holes) some ant activity between 20 and 100 cm
Human activity: a number of stones from stone circles up to 20 cm diameter in the surroundings

1) for abbreviations of species names and for explanation of cover values, see Part I,Ch. 2: Methods and Appendix 47

PROFILE DESCRIPTION

A 1.1 0-20 cm; 10 YR 5/2 when dry, 10 YR 3/2 when moist, clay loam; almost structureless when moist, massive; when dried up the horizon appears to consist of moderate to moderately strong fine subangular blocky clods, partially attached to the roots; slightly hard when dry, very friable when moist, slightly sticky and slightly plastic when wet; many micro and mesopores between the elements, only few pores through the elements; few large biopores; abundant fine, many medium roots; few very fine gravel (very coarse sandgrains); many fine and medium spherical, layered elements, hard or very hard when dry, firm when moist (dungbeetle balls?); few quartz pebbles and fragments; few larvae; one bone fragment at 12 cm; lower boundary gradual and wavy.

A 1.2 20-42 cm; 10 YR 5/2 when dry, 10 YR 4/2 when moist, loam; almost structureless, massive; slightly hard when dry, friable when moist, slightly sticky to sticky and slightly plastic when wet; many micropores, few mesopores (slightly spongy structure); common fine and medium roots; few very fine gravel; common fine and medium spherical elements above, few below, hard or very hard when dry, firm when moist; few quartz pebbles and fragments (flakes?); a number of ant(?) holes up to 2 inches diameter were recorded elsewhere in the pit; lower boundary gradual and smooth.

A C ca, sa 42-73 cm; 10 YR 5/3 when dry, 10 YR 4/3 when moist calcareous loam; structureless, massive; soft to slightly hard when dry, very friable when moist, slightly sticky and slightly plastic when wet; many micropores, few mesopores (slightly spongy structure); few very fine gravel; common fine roots above, few below; few fine and medium spherical elements; few quartz and quartzite fragments (flakes?); lower boundary gradual and smooth

C ca, sa 73-100 cm; 10 YR 6/3 to 6.5/3 when dry, 10 YR 5/4 when moist calcareous silt loam; structureless, massive; soft to slightly hard when dry, very friable when moist, slightly sticky and slightly plastic when wet; many micropores, few, but locally common mesopores; very few fine roots; few very fine quartz gravel (i.e.very coarse sand grains), few quartz and quartzite fragments (more common than in overlying horizons); few medium rounded lime concretions in the upper parts (10 YR 7-8/2 when dry), extremely hard when dry, increasing in number and size and becoming more and more irregularly shaped towards the lower boundary; lower boundary abrupt and wavy.

C 2 m deeper than 100 cm; calcareous hardpan, white (10 YR 7/2 to 8/2 when dry, locally with dark, almost black coatings; many very fine gravel included.

Remark: A fair number of chips and flakes was found at lower depth (ancient human activity)

Classification according to Soil Taxonomy (1975):

Diagnostic surface horizon:	Mollic epipedon
Diagnostic subsurface horizons:	-Calcic horizon (80-100 cm) -Petrocalcic horizon at 100 cm -Weak Cambic horizon
Other diagnostic characterisics:	Exchange complex dominated by amorphous materials
Soil moisture regime:	Ustic
Soil temperature regime:	Isothermic
Order:	Mollisols
Suborder:	Ustolls
Great Group:	Paleustolls
Subgroup:	Petrocalcic Paleustolls, saline phase
Family:	Thixotropic isothermic.

Profile Nr.14 (G.S.-Girtasho short grass spot)

GENERAL DATA

Area: Girtasho
Location: about 27.5 km SSW of Seronera, Serengeti National Park
Coördinates: 9705 N, 714 E (1:250,000 Serengeti Map)
Altitude: 1655 m
Described by: H.A. de Wit
Date: 16-11-1970
Weather condition: dry season, some rain before(?)
Aerial photo: Serengeti 1972, 3-99, L 11-S (Finn Map)
Physiography: halfway on the slope of a very gently sloping hill
Relief: subnormal
Slope: A-class, 1-3%, level and nearly level
Erosion: class 1?, sheet erosion may occur in some places
Parent material: clayey aeolian deposit
Landuse: National Park; grazing by game animals; extensive grazing by Masai cattle in the past (till 10 years ago)
Vegetation 1) : grassland site covered by short grasses (in Long grassland area); Dima 4, Miku 4, Eupa 3, Peme 3, Ttri 2, Arke 1, Pest +; Solincan 1, Dyschora +; total cover 45%
Drainage condition: well drained
Groundwater depth: not been established; very deep or absent
Moisture: dry throughout the profile
Salinity: 0-50 cm: non-saline; 50-70 cm: slightly saline; 70-140 cm: moderately saline; >140 cm slightly saline (G.S.I)
Root distribution: 0-120 cm; main mass 0-10(-40) cm
Biological activity: one animal hole at bottom of the pit, few large biopores; low, flattened termite mounds in the direct surroundings
Human activity: coarse fragments (granite mainly) from old stone circle
Stoniness: class 0
Permeability: moderate at the surface; in the natric horizon (9-32 cm) initially rapid, but rapidly decreasing to moderately slow; at 50 cm slow

1) for abbreviations of species names and for explanation of cover values, see Appendix 47 and Part I, Ch.2: Methods

PROFILE DESCRIPTION

A 1 (A 2?) 0-10 cm; 10 YR 4.5/2 when dry, 10 YR 3/1.5 when moist (silty) clay loam; almost structureless, massive layer which can be broken into variously sized and shaped clods with a tendency of weak thin platy elements near the surface (stratified material); slightly hard to hard locally when dry, friable when moist, slightly sticky and slightly plastic when wet; common micropores, few meso biopores; many fine, common medium roots; few very fine gravel; common very fine Fe? mottles along rootholes; few narrow cracks; lower boundary abrupt and smooth (locally wavy).

B 2.1.t 10-32 cm; 10 YR 4.5/1.5 when dry, 10 YR 3/1 whem moist (ped's surfaces, top) clay; strong medium (and coarse)compound columnar structure, which can be subdivided into strong medium prismatic above to fine prismatic below; very hard when dry, friable when moist, very sticky and plastic when wet; few micropores, few meso biopores (rootholes); common fine and medium roots; few very fine quartz gravel; all surfaces completely covered by dark shining coatings (10 YR 3/2 when dry, 10 YR 2.5/1 when moist), especially those of the smaller elements; common cracks between the columnar elements, up to 0.5 cm wide; some bleached material on the tops and along the upper sides of the columns ("albic interfingering"); lower boundary clear and smooth.

B 2.2.t, sa (ca) 32-65 cm; 10 YR 3/1.5 when dry, 10 YR 2.5/1 when moist (2/1 when rubbed, ped's surfaces), clay; weak coarse prismatic, easily subdivided into moderately strong very fine and fine angular blocky elements (grade of structure becomes less strong towards the lower horizon); slightly hard when dry, very friable when moist, sticky and plastic when wet; common fine roots, many old fine roots locally; few micropores, few meso and large biopores (only few rootholes between the fine structure elements); few very fine gravel (quartz); common fine, light brownish gray, round lime concretions (10 YR 6/2 when dry), extremely hard when dry, some with some very fine gravel included; coatings on all the ped's surfaces, 10 YR 3/1 when dry; few medium and large biopores with shining plastered inner walls; strong reaction on $CaCO_3$ by use of HCl (concretions); lower boundary gradual and smooth.

B 3 ca, sa 65-110 cm; 10 YR 3.5/2 when dry, 10 YR 3/1-1.5 when moist above to 10 YR 5/3 when dry, 10 YR 3/2.5 when moist near lower boundary, (silty) clay loam; weak structure, almost massive, falling apart into moderate fine angular blocky when dry and when disturbed; slightly hard when dry, very friable when moist, sticky and plastic when wet above to sticky and slightly plastic below; common micropores above, many near lower boundary, few meso and large biopores above, common mesopores near lower boundary; common fine roots above to few below; common very fine gravel above; near upper boundary common round very fine and fine lime concretions, extremely hard when dry, decreasing in number towards the lower boundary; from 110 cm downwards, medium white (10 YR 8/2 when dry) irregularly shaped lime concretions were recorded, increasing in size and number towards the lower boundary; many very dark gray to black coatings on the ped's surfaces in the upper parts, many fine very dark gray to black clayey elements in the lower parts of the horizon; walls of biopores with black coatings on their inner side; strong reaction on $CaCO_3$ by HCl; many fine distinct mottles (10 YR 6/6 when dry), causing the more yellow colours of the lower parts of the horizon; lower part of the horizon moderately saline; lower boundary clear and smooth.

C ca, sa 110-150 cm (bottom of pit); 10 YR 5/4 to 6/4.5 when dry, 10 YR 4/3 when moist loam; structureless, massive; slightly hard to hard when dry; common very fine gravel; many medium and coarse white (10 YR 8/2 when dry, inside) lime concretions, irregularly shaped, extremely hard when dry, form a major part of this horizon; strong reaction on $CaCO_3$ by HCl; moderately saline.

Remark: There might be one more boundary in the horizon between 65 and 120 cm; changes in colour and texture, however, were very gradual.

Classification of profile nr. 14 according to Soil Taxonomy (1975):

Diagnostic sutface horizon: Mollic epipedon (after mixing the upper 18 cm)
Diagnostic subsurface horizons: -Natric horizon
-Cambic horizon
Other diagnostic characteristics: -Amorphous materials form the greater part of the exchange complex

Soil moisture regime:	Ustic
Soil temperature regime:	Isothermic
Order:	Mollisols
Suborder:	Ustolls
Great Group:	Natrustolls
Subgroup:	Typic Natrustolls
Family:	(Very) fine, mixed over thixotropic (calcareous), isothermic.

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Profile Nr.15 (G.L.-Girtasho tall grass spot)

GENERAL DATA

Area: Girtasho
Location: about 27.5 km SSW of Seronera, Serengeti National Park
Coördinates: 9705 N, 714 E (1:250,000 Serengeti Map)
Altitude: 1655 m
Described by: H.A.de Wit
Date: 27/28-11-1970
Weather condition: dry season, some rain on days before
Aerial photo: Serengeti 1972, 3-99, L 11-S (Finn map)
Physiography: halfway on the slope of a very gently sloping hill
Relief: subnormal
Slope: A-class, 1-3 %, level and nearly level
Erosion: class 1, sheet erosion occurs locally
Parent material: clayey aeolian deposit
Landuse: National Park; grazing by game animals; extensive grazing by Masai cattle in the past
Vegetation 1) : long grassland, burned about 1 month before, now recovering (greening); profile in long grassland spot; dominant species: Ttri 5, Dima 2, Eupa 3, Peme 3, Miku 2, Pest 3; Solincan, Sidovata, Justexig, Helisteu in direct surroundings
Drainage condition: well drained
Groundwater depth: not established; very deep or absent
Moisture: slightly moist below 0.90 m
Salinity: non-saline throughout the profile
Root distribution: 0-155 cm, main mass 0-40 cm
Biological activity: few meso biopores in surface soil, few larvae
Human activity: -
Stoniness: class 0
Permeability: moderately rapid throughout

1) for abbreviations of species names and explanation of cover values, see Appendix 47 and Part I Ch.2 : Methods

PROFILE DESCRIPTION

A 1 — 0-8 cm; 10 YR 4/1.5 to 4/2 when dry, 10 YR 3/1 to 3/1.5 when moist clay; partially almost structureless, massive, partially moderate fine and medium subangular blocky (attached to the roots); slightly hard to hard when dry, friable when moist, sticky and slightly plastic when wet; common micropores, few meso biopores; many fine and medium roots; few very fine gravel; few fine worm? excrements; few dark coatings on surfaces of elements near the lower boundary; lower boundary gradual and wavy.

B2.1 t — 8-35 cm; 10 YR 3/1.5 when dry, 10 YR 2/1 when moist, clay; moderate coarse prismatic which falls apart into strong very fine angular blocky elements when dry; hard when dry, firm when moist, very sticky and plastic when wet; few micro, common meso biopores; common fine and medium roots; common very fine quartz gravel (very coarse sand grains); common medium (5-7 mm diam.) spherical elements with peeling walls (dungbeetle balls?); few fine worm? excrements; few fine insect eggs; many black (10 YR 2/1 when dry) coatings (clayskins) on all the ped's surfaces; cracks up to 3 mm wide; lower boundary gradual and smooth.

B 3 80(70)-100(90) cm; 10 YR 4/2.5 when dry; 10 YR 3/2.5 when moist, clay (above) to clayloam (below); weak coarse prismatic above, massive and structureless, massive below; slightly hard to hard when dry, friable when moist; slightly plastic and slightly sticky when wet; common to many micropores, common meso biopores; common fine roots; few very fine gravel; common fine insect eggs; one single medium sized transparent quartz fragment; common dark skin-like mottles (10 YR 3/2 when dry); common fine and medium light gray powdery spots (10 YR 7/2 when dry), soft when dry; few narrow cracks present; lower boundary gradual and smooth.

C 100(90)-120(110) cm; 10 YR 4.5/3 to 5/3 when dry, 10 YR 3/2.5 when moist, silt loam; structureless, massive; slightly hard when dry, friable when moist, slightly sticky and slightly plastic when wet; many micro, common mesopores; common fine roots, but less common than in overlying horizon; few very fine gravel; common fine light gray (10 YR 7/2 when dry) powdery spots; below 110 cm there was a clear reaction on the occurrence of $CaCO_3$ when HCl was added; lower boundary clear and wavy.

C 2 ca 120(110)-160 cm (bottom of pit); 10 YR 5/5 to 6/5 when dry, 10 YR 3/4 when moist (crushed and rubbed) calcareous loam; matrix structureless and loose, the greater part of its horizon consists of medium and coarse subangular and rounded elements of cemented soil material; elements are hard to very hard when dry, firm when moist, slightly sticky and slightly plastic when wet (soil material crushed and rubbed), elements become harder at lower depth; common micropores, few mesopores (elements); few fine roots to a depth of 150 cm; few very fine gravel (quartz); many fine and medium distinct white lime veins locally pseudo-mycelium-like in the hard elements and on their surfaces; many very fine (up to 1 mm diameter) round white lime, pockets in the elements; common white medium and coarse lime concretions, extremely hard when dry, in increasing amount towards the bottom of the pit; below many light brownish gray (10 YR 6/2 when dry) irregularly shaped, sometimes banded medium and coarse limestóne concretions, extremely hard when dry; in all parts of this horizon was a strong reaction on the occurrence of $CaCO_3$ (HCl).

Remark: Boundaries between the horizons distinguished are mostly gradual to diffuse; distinction between them has been made mainly on structural differences. Changes in colour were very gradual, especially between 70 and 120 cm and did not quite correspond with the changes in soil structure.
The same remark can be made with relation to the boundary below which free $CaCO_3$ occurred (110 cm).

Classification according to Soil Taxonomy (1975):

Diagnostic surface horizon :	Mollic epipedon
Diagnostic subsurface horizons:	Argillic horizon
	Cambic horizon
Other diagnostic characteristics:	-Amorphous material form the greater part of the exchange complex
	-Cracks up to 15 mm wide between 35-80 cm
	-Clay content over 35% throughout the greater part of the profile
	-COLE of about 0.07 at 50-60 cm
Soil moisture regime:	Ustic
Soil temperature regime:	Isothermic
Order	Mollisols
Suborder	Ustolls
Great Group:	Argiustolls
Subgroup:	Vertic Argiustoll

Family: (very)fine, mixed over thixotropic (calcareous), isothermic.

Textural data, organic carbon and lime contents, P (citric acid) and N (total soil) for soils of Soil landscape I.3, according to Oosterbeek methods (see Part I, Ch.2: Methods)

	%of total soil		% of total mineral fraction									
Profile, depths	org.C	$CaCO_3$	<2µm	2-16µm	16-50µm	50-105µm	105-150µm	150-210µm	210-300µm	>300µm	P	N
G.T.III												
0-10	5.2	0.3	34.1	19.6	19.3	7.4	4.4	2.3	2.0	10.9	462	0.27
20-30	3.3	0.7	20.7	19.9	22.0	9.8	6.2	3.5	2.8	15.1		
50-60	3.0	5.8	14.6	23.3	17.6	13.1	7.9	4.2	3.2	16.1		
80-90	4.2	17.5	14.3	18.5	23.6	12.9	8.0	4.5	3.2	15.0		
G.S.III												
0- 9	4.2	0.3	28.9	26.4	21.7	6.8	4.3	2.0	1.5	8.4	194	0.18
9-20	1.6	0.2	61.1	12.1	12.6	3.8	2.4	1.2	1.0	5.8		
20-30	1.0	0.3	60.7	13.6	12.6	3.3	2.3	1.2	1.0	5.3		0.10
40-50	1.4	1.2	59.1	19.6	10.8	2.6	1.7	1.0	0.8	4.4		
80-90	3.0	0.8	31.1	29.2	20.6	3.4	2.8	1.7	1.3	9.9		
110-120	3.4	1.4	20.4	32.9	20.0	7.4	5.5	3.5	2.3	8.0		
140-150	3.7	6.5	16.9	28.4	12.5	11.3	9.6	7.0	4.5	9.8		
20-30[2])		0.0	60.0	19.6	9.0	2.9	2.2		6.3			
G.L.II												
0-10	5.7	0.4	44.7	19.0	20.2	3.2	3.5	1.7	1.4	6.3	206	0.27
20-30	2.7	0.3	57.3	15.4	12.2	5.1	2.0	1.3	1.9	4.8		0.14
40-50	1.4	0.2	62.4	14.5	9.3	3.6	2.2	1.2	1.0	5.8		
60-70	1.0	0.4	64.1	14.2	7.6	3.4	3.5	1.1	0.9	5.2		
80-90	0.5	0.3	60.2	19.8	7.8	3.5	2.1	1.1	0.9	4.7		
110-120	3.8	0.8	21.6	36.2	18.7	3.5	3.0	2.2	1.8	13.0		
140-150	3.6	4.4	24.8	28.9	13.6	7.5	5.4	4.5	3.5	11.8		
G.V.												
0-10	6.1	0.3	67.2	15.6	10.7	2.7	1.3	0.6	0.5	1.4		0.29
20-30	1.4	0.2	70.1	14.5	8.3	1.2	1.5	0.9	0.8	2.7		
40-50	0.2	0.3	69.0	14.0	7.7	2.4	1.4	0.8	0.8	3.9		
80-90	0.0	0.3	71.4	13.6	4.8	2.2	1.3	0.8	0.7	5.2		
128-140	2.6	2.8	28.6	27.3	16.0	2.2	2.4	2.0	2.1	19.3		
80-90[2])		0.2	73.8	11.0	6.6	1.7	1.3		5.5			

[1]) by loss on ignition

[2]) samples pre-treated with Na-EDTA

Soil Landscape I.3 ("Long Grasslands"): mean infiltration rates (mm/h)

profile, depths (cm)	Exp.[1]	n[2]	mean infiltr. rate	lowest value	highest value	mm infiltr. (averages)
GT III (Ridge top)						
Surface	I	10	64.1	37.8	106.5	12.43
	II	10	42.3	22.8	53.6	12.43
	III	10	42.8	22.8	57.0	12.43
	IV	10	42.4	21.7	58.9	12.43
26/27 cm	I	7	340.2	175.5	596.6	12.43
	II	7	118.0	79.9	175.5	12.43
	III	7	111.4	73.4	218.3	12.43
	IV	7	127.0	72.2	344.2	12.43
	V	7	95.1	72.2	126.1	12.43
	VI	7	93.5	71.6	124.3	12.43
CS III (Flank, short grass spot)						
Surface	I	10	66.1	25.3	298.3	12.43
	II	10	23.0	15.6	53.3	12.43
	III	10	21.3	16.1	30.8	12.43
	IV	10	20.5	15.4	29.3	12.43
3 cm	I	5	58.0	32.4	102.9	12.43
	II	5	35.6	20.5	56.3	12.43
	III	5	37.8	21.6	63.5	12.43
	IV	5	38.2	19.6	64.9	12.43
10 cm	I	5	760.7	298.3	1118.7	12.43
	II	5	361.6	76.5	745.8	12.43
	III	5	140.7	20.4	389.1	12.43
	IV	5	62.3	14.7	154.3	12.43
	V	5	33.0	12.5	70.5	12.43
	VI	5*	18.9	6.8	48.1	12.43
20 cm	I	3	9324.0	5594.0	11189.0	31.08
	II	3	4041.3	1066.0	6582.0	31.08
	III	3	2429.3	360.9	3730.0	31.08
	IV	3	1725.0	139.8	2797.0	31.08
	V	3	1080.3	87.7	2034.0	24.86
	VI	3	655.4	57.4	1598.0	24.86
47.5 cm	I	3	35.7	17.3	55.9	6.21
	II	3	17.9	± 0	34.4	6.21
	III	3	13.6	± 0	23.3	6.21
	IV	3	10.8	± 0	22.9	6.21

profile, depths (cm)	Exp.[1]	n[2]	mean infiltr. rate	lowest value	highest value	mm infiltr. (averages)
GL II (Flank, tall grass spot)						
Surface	I	10	593.3	110.5	1278.5	12.43
	II	10	132.9	34.0	263.2	12.43
	III	10	113.8	19.7	263.2	12.43
	IV	10	107.4	16.8	255.7	12.43
	V	10**	102.9	16.8	241.9	12.43
	VI	10**	100.1	16.8	235.5	12.43
3 cm	I	5	392.1	179.0	688.4	12.43
	II	5	149.5	73.4	358.0	12.43
	III	5	115.7	60.9	288.7	12.43
	IV	5	106.1	50.3	271.2	12.43
	V	5	91.2	43.2	235.5	12.43
21 cm	I	3	177.6	95.1	298.1	6.21
	II	3	101.7	55.2	165.6	6.21
	III	3	92.4	53.2	154.2	6.21
	IV	3	81.4	52.6	127.8	6.21
	V	3	81.0	50.2	135.5	8.29
	VI	3	72.5	46.9	120.8	8.29
52/55 cm	I	4	7.9	4.5	12.9	5.05
GV (Valley bottom)						
Surface	I	9	765.4	389.1	1278.5	12.43
	II	9	452.5	229.5	639.3	12.43
	III	9	422.5	124.3	688.4	12.43
	IV	9	377.5	131.6	745.8	12.43
	V	9	348.3	100.6	745.8	12.43
	VI	9	339.8	79.9	813.6	12.43
	VII	9**	324.4	79.9	813.6	12.43
Surface'	I'	6	380.9	84.4	895.0	12.43
	II'	6	240.0	60.9	688.4	12.43
	III'	6	[illegible]	51.4	497.2	12.43

1) Number of infiltration experiment
2) Number of rings used
* one figure lacking; last known lowest rate filled.
** ditto, but 2 or 3 figures missing.

Appendix 37

depth (cm)	SP	pH_p	pH_e	EC_e	Na^+	K^+	$Ca+Mg^{2+}$	Sum +	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Sum -	% Lime
					all in meq/1 of the sat.extracts										
Simba-east, erosion scarp															
0- 1	20.7	9.89	9.80	55.0	662.6	97.0	< 2.0	759.6	54.4	51.2	323.1	338.1	7.5	743.3	-
1- 5	18.0	10.17	10.10	136.0	2700.0	316.1	< 2.0	3016.1	206.3	78.3	1252.2	1434.1	87.5	3058.4	0.88
5- 10	27.1	10.25	10.16	112.0	1904.4	214.8	"	2119.2	189.2	60.9	924.1	843.9	50.0	2068.1	1.84
20- 30	39.5	10.29	10.20	58.0	740.9	85.3	"	826.2	105.8	41.6	385.3	263.9	15.0	811.6	4.44
30- 40	41.5	10.18	10.13	49.5	598.7	73.7	"	672.4	104.6	43.7	302.0	205.8	12.5	668.6	5.19
40- 50	39.3	10.21	10.17	45.6	543.9	68.6	"	612.5	90.5	43.7	264.9	191.2	12.5	602.8	5.34
Simba-east, ridge top															
0- 20	50.1	6.61	7.50	0.53	1.30	2.61	1.28	5.19		3.20					0.16
20- 40	51.8	7.92	8.30	8.00	52.61	22.86	3.45	78.92		6.30					0.76
40- 60	43.2	9.59	9.63	21.50	186.52	65.68	-	252.20		72.45					2.23
60- 80	43.4	9.58	9.60	27.00	254.35	77.80	-	332.15		91.43					5.11
80-100	43.2	9.51	9.52	25.70	246.52	73.66	-	320.18		94.08					13.79
100-115	40.9	9.57	9.58	27.00	260.87	75.96	-	336.83		94.49					17.62
Ngare nanyuki, ridge top															
0- 20	32.9	6.67	8.03	0.43	0.87	1.52	1.56	3.95		3.22					0.26
20- 40	32.7	7.72	8.47	0.58	1.53	2.49	1.56	5.58		4.77					2.07
40- 60	34.2	8.45	8.75	2.35	9.52	10.20	1.15	20.87		6.57					8.18
60- 80	36.4	9.66	9.72	9.30	58.70	37.60	0.47	96.77		59.13					13.34
80-100	36.8	9.87	9.89	17.30	135.21	65.22	0.51	200.94		128.35					15.74
100-110	35.7	10.07	10.04	24.30	218.26	81.33	0.44	300.03		183.61					12.52
Ngare nanyuki, valley															
0- 20	45.6	6.57	8.21	0.45	1.48	1.00	1.57	4.05		2.63					0.22
20- 40	52.1	6.92	8.38	0.47	2.78	0.80	0.95	4.53		2.56					0.17
40- 60	51.8	7.52	8.62	0.76	6.48	0.61	0.81	7.90		5.39					0.51
60- 80	46.4	7.85	8.80	1.03	10.43	0.44	0.68	11.55		7.61					2.10
80-100	46.3	8.13	8.90	1.34	13.13	0.42	0.37	13.92		9.47					6.08

G.L. I (flank, tall grass spot)

depth (cm)	SP	pH_p	pH_e	EC_e	Na^+	K^+	Ca^{2+}	$Ca+Mg^{2+}$	Sum +	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Sum -
0– 10	64.4	6.14	7.21	0.92	0.97	2.41	3.93	6.51	9.89	-	7.44	0.94	0.58		8.96
10– 20	63.1	5.91	7.11	0.70	1.01	1.98	2.95	4.49	7.48	-	5.98	0.64	0.42		7.04
20– 30	71.8	5.99	7.42	0.42	0.69	1.35	1.64	2.41	4.45	-	3.53	0.50	0.38		4.41
30– 40	72.0	6.11	7.63	0.40	0.73	1.22		2.11	4.06	-	2.59	1.01	0.30		3.90
40– 50	74.3	6.26	7.71	0.38	0.85	1.09	1.44	2.11	4.05	-	3.11	0.47	0.30		3.88
50– 60	77.1	6.46	8.10	0.37	1.01	0.91		1.86	3.78	-	3.15	0.37	0.06		3.58
60– 70	71.5	6.52	8.19	0.32	1.09	0.74	0.95	1.37	3.20	-	2.32	0.44	0.14		2.90
70– 80	64.3	6.72	8.33	0.24	1.03	0.54		0.81	2.38	-	1.38	0.54	0.20		2.12
80– 90	66.9	6.88	8.35	0.35	1.57	0.67	0.88	1.27	3.51	-	2.59	0.50	0.18		3.27
90–100	62.6	7.04	8.50	0.42	1.93	0.72		1.63	4.28	-	3.25	0.47	0.34		4.06
100–110	58.5	7.25	8.50	0.47	2.19	0.78	1.38	1.89	4.86	-	3.73	0.60	0.38		4.71
110–120	52.5	7.44	8.58	0.47	2.17	0.82		1.79	4.78	-	3.56	0.57	0.40		4.53
120–130	49.2	7.47	8.56	0.50	2.42	0.93	1.18	1.73	5.08	-	3.67	0.70	0.58		4.95
130–140	53.1	7.57	8.59	0.50	2.66	0.99		1.37	5.02	-	3.49	0.70	0.66		4.85
140–150	52.7	7.64	8.58	0.55	3.18	1.09	0.79	1.30	5.57	-	3.84	0.74	0.74		5.32

G.S. I (flank, short grass spot)

depth (cm)	SP	pH_p	pH_e	EC_e	Na^+	K^+	Ca^{2+}	$Ca+Mg^{2+}$	Sum +	CO_3^{2-}	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	Sum -
0– 10	40.7	6.46	8.17	0.96	7.00	1.08	0.88	1.56	9.64	-	6.81	1.78	1.07	-	9.66
10– 20	74.6	6.98	8.68	1.28	11.65	0.75		0.59	12.99	-	9.44	3.02	0.97	-	13.43
20– 30	75.5	7.95	8.90	1.86	16.87	0.67	0.49	0.68	18.22	-	7.99	8.86	1.38	-	18.23
30– 40	74.7	8.15	8.82	3.78	32.17	0.92		0.85	33.94	-	5.78	24.66	5.69	-	36.13
40– 50	79.8	8.20	8.65	6.30	58.26	1.47	1.18	1.99	61.72	-	4.60	40.87	16.03	-	61.50
50– 60	75.4	8.19	8.50	7.20	70.00	1.84		2.34	74.18	-	3.98	45.91	24.10	-	73.99
60– 70	72.5	8.21	8.44	7.70	73.92	2.02	1.47	2.51	78.45	-	3.60	47.01	27.62	-	78.23
70– 80	68.4	8.17	8.33	8.80	83.92	2.31		3.19	89.42	-	3.22	55.87	30.83	0.25	89.92
80– 90	69.0	8.12	8.33	9.40	89.57	2.47	2.36	3.74	95.78	-	2.90	64.33	29.79	0.50	97.02
90–100	49.6	8.01	8.25	11.10	105.22	2.93		5.24	113.39	-	2.56	79.13	34.45	0.75	115.14
100–110	61.1	7.90	8.18	11.40	109.57	3.31	3.63	5.86	118.74	-	2.52	84.76	33.31	1.00	120.59
110–120	61.1	7.92	8.12	11.20	107.83	3.10		5.92	116.85	-	2.42	84.06	31.55	2.00	118.03
120–130	60.4	7.95	8.31	10.00	97.40	2.95	3.41	5.40	105.75	-	2.59	73.89	28.24	2.00	89.75
130–140	55.5	7.89	8.32	8.70	81.74	2.76		4.62	89.12	-	2.94	59.40	27.41	2.00	89.75
140–150	57.8	7.92	8.37	7.00	65.65	2.36	2.06	3.32	71.33	-	3.01	46.31	22.03	2.00	71.35

Appendix 41

	SP	pH_p	pH_e	EC_e	Na^+	K^+	Ca^{2+}	$Ca+Mg^{2+}$	Sum +	CO_3^{2-} $+HCO_3$	% Lime
SAM N 1 (ridge top, relatively short grasses with *Digitaria macroblephara* dominant)											
						all meq/1 of the sat. extracts					
0- 20	41.0	6.58	8.24	0.52	0.92	2.02	1.73	2.22	5.16	3.13	0.25
20- 40	48.9	6.55	7.90	0.35	0.83	1.38		1.14	3.35	1.68	0.50
40- 60	52.5	6.90	8.25	0.36	0.92	1.60	0.76	0.91	3.43	1.65	0.65
60- 80	49.9	7.70	8.66	0.70	2.61	2.96		1.34	6.91	4.19	1.05
80-100	42.4	7.95	8.80	1.32	6.96	5.09	1.17	1.91	13.96	6.67	4.68
100-120	39.1	8.18	-	1.30				0.50		7.01	6.20
SAM N 2 (ridge top, *Pennisetum mezianum* spot)											
0- 20	46.5	6.74	8.22	0.68	1.02	2.13		3.83	6.98	4.81	0.55
20- 40	50.1	6.45	8.01	0.36	0.87	1.03		1.71	3.61	1.92	0.51
40- 60	53.3	6.65	8.21	0.34	0.89	0.86		1.61	3.36	1.51	0.28
60- 80	51.8	7.20	8.35	0.49	1.37	1.05		2.82	5.24	3.44	0.43
80-100	45.9	7.68	8.51	0.47	1.42	0.94		2.42	4.78	2.75	4.08
100-110	41.5	7.77	8.61	0.59	2.15	1.46		2.57	6.18	3.30	7.98
Loliok 1 (ridge top, shorter grasses, lower cover)											
0- 20	34.3	6.47	8.16	0.52	0.75	2.55		2.22	5.52	2.54	0.02
20- 40	36.1	6.58	8.03	0.47	0.81	2.96		1.51	5.28	1.72	0.00
40- 60	44.1	6.93	8.08	0.72	1.18	3.99		1.01	6.18	2.68	0.23
60- 80	44.4	7.89	8.76	1.80	3.78	11.05	1.32	1.31	16.14	6.87	0.60
80-100	44.7	8.29	8.85	2.50	6.37	16.07	1.02	1.26	23.71	7.15	3.54
Loliok 2 (ridge top, taller grasses, higher cover)											
0- 20	36.3	6.40	8.21	0.51	0.66	2.46	1.93	2.02	5.14	2.75	0.31
20- 40	38.6	6.45	7.85	0.42	0.64	2.46	1.02	1.41	4.51	1.79	0.15
40- 60	46.0	6.70	8.03	0.48	0.80	4.74		2.22	7.76	2.65	0.22
60- 80	49.6	7.60	8.68	1.08	2.18	7.38	0.71	0.91	10.47	7.15	0.54
80-100	39.6	8.17	8.90	1.50	3.74	10.91	0.51	0.65	15.30	8.52	2.07

depth (cm)	SP	pH_p	pH_e	EC_e	Na^+	K^+	Ca^{2+}	Ca+Mg	Sum +	$CO_3^{2-}+$ HCO_3^-	Cl^-	SO_4^{2-}	NO_3^{2-}	Sum −	% Lime
SAM K 1 (lower flank, tall grass spot)															
								all in meq/1 of the sat.extracts							
0- 10	49.0	6.41	8.41	0.35	0.45	1.84	0.86	1.02	3.31	2.08	0.63	0.48	-	3.19	0.17
10- 20	53.0	6.35	8.21	0.24	0.43	1.50		0.79	2.72	1.31	0.53	0.52	-	2.36	0.00
20- 30	56.5	6.41	8.07	0.26	0.49	1.41		0.59	2.49	1.06	0.13	0.96	0.50	2.65	0.24
30- 40	56.2	6.53	8.12	0.35	0.69	1.71	0.66	0.99	3.39	1.06	0.16	0.67	1.00	2.89	0.22
40- 50	55.7	6.85	8.52	0.43	1.23	1.91		1.12	4.26	1.84	0.40	0.62	1.00	3.86	0.15
50- 60.	51.6	7.33	8.22	0.49	1.34	2.30	1.23	1.48	5.12	4.14	0.26	0.56	-	4.96	0.24
60- 70	49.8	7.66	8.31	0.52	1.65	2.48		1.15	5.28	4.14	0.30	0.79	-	5.23	0.89
70- 80	51.6	7.79	8.29	0.64	2.39	3.06	0.79	0.99	6.44	4.52	0.49	1.21	-	6.22	1.64
90-100	52.8	7.83	8.11	0.75	3.57	3.23		0.69	7.49	4.98	0.39	1.48	-	6.85	2.33
110-120	51.6	7.98	8.27	0.91	5.61	3.12	0.50	0.79	9.52	6.10	0.52	2.41	-	9.03	6.00
SAM K 2 (lower flank, short grass spot)															
0- 10	49.3	6.87	8.31	0.85	1.23	3.45	2.25	3.98	8.66	5.79	1.28	1.37	-	8.44	0.40
10- 20	53.3	6.88	8.29	1.05	2.00	3.99	1.99	3.88	9.87	3.09	5.48	0.96	-	9.53	0.19
20- 30	55.5	7.03	8.45	0.85	2.17	3.51		2.40	8.08	4.21	2.52	1.19	-	7.92	0.22
30- 40	56.4	7.25	8.55	0.88	3.39	3.43	1.19	1.84	8.66	5.16	1.93	1.29	-	8.38	0.15
40- 50	55.5	7.56	8.81	1.10	5.74	4.01		1.71	11.46	6.87	2.33	1.97	-	11.17	0.23
50- 60	56.1	7.99	8.79	1.60	9.00	5.03	1.25	1.97	16.00	8.28	4.92	2.29	-	15.49	0.32
60- 70	55.5	8.11	8.68	2.62	16.74	6.79		1.91	25.44	6.24	15.74	2.73	-	24.71	0.76
70- 80	57.2	8.07	8.44	5.30	34.35	10.82	1.99	3.88	49.05	4.03	43.57	1.98	-	49.58	1.26
90-100	56.5	7.94	8.13	16.80	130.44	22.82	8.94	19.54	172.80	2.38	143.51	15.50	6.00	167.39	1.72
110-120	55.9	7.78	7.95	26.40	220.68	25.13	25.69	52.89	298.90	1.82	219.54	67.71	10.00	299.07	1.44

Appendix 43

profile, depths (cm)	SP	pH_p	pH_e	EC_e	Na^+	K^+	$Ca+Mg^{2+}$	Sum +	HCO_3^- + CO_3^{2-}	NO_3^-	% Lime
					all concentrations in meq/l of the sat.extract						
NaNo I											
0– 20	62.0	6.49	8.13	0.36	0.87	1.10	1.75	3.72		–	0.16
20– 40	50.8	6.79	8.28	0.31	0.92	0.96	1.32	3.20	1.94	–	0.13
40– 60	53.0	7.43	8.67	0.51	2.20	1.65	1.62	5.47	4.08	–	1.18
60– 80	47.8	8.17	8.90	1.83	15.26	3.05	0.67	18.98	8.85	≈0	5.72
80–100	45.1	8.79	9.09	4.16	38.26	6.83	1.05	46.14	21.23	0.25	
100–115	41.6	8.95	9.08	9.50	67.83	10.74	1.28	79.85	26.35	≈0	20.05
NaNo II											
0– 20	59.4	6.59	8.15	0.51						–	
20– 40	50.6	6.87	8.26	0.35						–	
40– 60	52.4	7.74	8.69	1.15						–	
60– 80	49.2	9.45	9.56	9.00						–	
80–100	46.7	9.66	9.77	14.80						≈0	
100–120	42.6	9.75	9.83	15.10						0.50	
NaNo III											
0– 20	55.6	6.66	7.72	0.55						–	
20– 40	55.6	7.11	7.95	1.15						0.25	
40– 60	57.4	8.01	8.26	22.00						2.50	
60– 80	50.1	9.48	9.55	27.20						3.00	
80–100	48.5	9.53	9.58	23.00						2.00	
100–120	42.9	9.53	9.59	23.00						1.00	
NaNo IV											
0– 20	50.5	7.60	8.21	0.70	1.72	1.84	3.04	6.60	2.77	2.00	
20– 40	50.3	7.50	7.68	8.80	45.22	7.67	27.67	80.56	3.11	3.00	
40– 60	50.9	8.23	8.36	29.60	320.00	22.32	17.93	360.30	7.26	17.50	
60– 80	48.8	9.18	9.20	29.60	419.13	28.77	1.35	449.25	53.32	12.50	
80–100	47.9	9.67	9.72	25.50	282.61	30.69	0.61	313.91	105.39	6.00	
100–120	43.9	9.65	9.68	24.60	276.52	30.31	0.51	307.34	119.09	3.00	
NaNo V											
0– 20	50.3	8.03	8.51	0.78	5.26	1.44	1.35	8.05	4.91	–	1.08
20– 40	52.1	8.10	8.45	2.46	18.43	1.99	2.09	22.51	1.04	–	0.43
40– 60	53.2	7.71	8.24	9.90	81.74	6.41	13.26	101.41	1.14	15.00	0.73
60– 80	49.7	9.12	9.23	12.30	123.48	9.67	1.62	134.77	25.73	17.50	2.55
80–100	46.5	9.34	9.44	10.20	102.61	10.05		112.66	50.41	12.50	
100–120	44.4	9.59	9.61	15.90	175.65	18.18	0.81	194.64		7.50	16.70
NaNo VI											
0– 20	59.1	6.50	8.09	0.41	0.98	1.40	1.82	4.20	2.77	–	0.59
20– 40	49.1	6.75	8.48	0.45	2.91	1.00	0.51	4.42	2.94	–	0.00
40– 60	48.2	7.95	8.90	1.33	12.44	1.80	0.44	14.68	12.07	–	3.27
60– 80	42.2	8.48	9.01	1.94	18.91	2.88	1.08	22.87	18.36	≈0	7.82
80–100	40.0	8.71	9.10	2.42	23.04	2.88	2.02	27.94	20.75	0.25	18.07
NaNo VII											
0– 20	61.2	6.52	8.06	0.47						–	
20– 40	51.9	6.62	8.44	0.45						–	
40– 60	50.2	7.93	9.00	1.59						–	
60– 80	45.0	8.68	9.19	3.12						≈0.0	
80–100	42.4	9.14		4.57						0.25	
NaNo VIII											
0– 20	56.5	7.24	8.39	0.64						–	
20– 40	49.1	7.19	8.78	0.76						–	
40– 60	45.2	9.00	9.36	4.08						+1)	
60– 80	46.6	9.16	9.45	5.60						+1)	
80–100	43.8	9.38	9.56	5.40						+1)	
NaNo IX											
0– 20	48.5	7.86	8.51	1.05					9.61	0.50	1.47
20– 40	53.6	7.97	8.59	2.17	16.35	2.16	2.83	21.34	4.88	12.50	0.33
40– 60	49.4	7.45	8.06	9.00	63.26	5.60	22.94	91.80	2.07	87.50	0.00
60– 80	51.2	8.20	8.64	5.62	48.70	4.53	2.16	55.39	5.29	50.00	1.91
80–100	46.7	8.80	9.04	5.66	57.48	5.14	0.64	63.46	16.18	40.00	5.11
100–120	44.0	9.02	9.20	8.20	80.00	8.52	–	88.52	–	35.00	14.57

1) accurate determination not feasible because of too dark colours of the extract

Profile code Sender *H.A. de Wit* Project *SERENGETI PLAIN* no.

texture

19								
fraction: µm	%	%	%	%	%	%	%	%
>2000								
1000-2000								
500-1000								
250-500								
100-250								
50-100								
2-50								
< 2								

19	classification
	TS : Total Soil

19																
fraction: µm	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
1650-2000																
1190-1650																
850-1190																
600-850																
420-600																
300-420																
210-300																
150-210																
105-150																
75-105																
50-75																
32-50																
16-32																
8-16																
4-8																
2-4																
< 2																

elemental analysis — weight percentage (*T.S* < 2 mm; *Ba clay* < 2 µm)

19 Depths (cm)	0-15		15-32		32-45		67-80		92-105		0-10		20-30		50-60	
SiO_2	78.68	40.63	67.23	40.49	63.65	41.23	64.33	41.99	63.33	42.86	61.21	51.17	56.74	43.33	52.21	40.13
Al_2O_3	8.22	21.65	14.19	23.68	15.18	21.95	15.29	20.88	15.60	20.63	9.30	13.35	10.60	14.61	11.92	16.64
Fe_2O_3	3.03	10.89	5.64	10.14	6.00	9.53	6.03	9.26	6.31	9.11	5.96	6.70	6.79	7.23	7.27	7.67
FeO																
MnO	0.08	0.23	0.08	0.12	0.09	0.13	0.09	0.13	0.16	0.16	0.22	0.16	0.21	0.23	0.22	0.26
MgO	0.31	0.96	0.63	0.74	0.71	1.06	0.83	0.98	0.90	0.99	1.24	1.08	1.65	1.81	2.18	2.14
CaO	1.60	0.26	1.67	0.10	2.33	0.22	2.04	0.36	1.77	0.32	4.88	1.66	6.71	3.75	7.80	3.42
Na_2O	n.d.	0.44	n.d.	0.23	n.d.	0.33	n.d.	0.21	n.d.	0.27	n.d.	0.25	n.d.	0.30	n.d.	0.43
K_2O	1.87	2.34	1.47	1.98	2.02	1.83	2.02	1.84	2.01	1.87	2.40	2.03	3.13	2.48	4.00	3.31
TiO_2	0.92	1.62	1.01	1.16	1.15	1.00	1.13	1.04	1.20	1.03	1.72	0.78	1.99	0.82	2.05	0.88
P_2O_5	0.35	0.89	0.31	0.46	0.39	0.49	0.47	0.52	0.42	0.47	2.06	2.04	3.36	3.54	2.19	1.90
BaO		3.61		4.20		4.04		3.82		3.60		4.27		4.57		4.89
H_2O^+	3.94	16.51	7.30	16.39	7.11	17.79	7.42	18.50	7.10	17.60	10.82	16.19	7.40	16.65	8.03	18.66
Σ	99.00	100.03	99.53	99.69	98.63	100.00	99.65	99.53	98.80	98.91	99.81	99.68	98.58	99.32	97.87	100.33
	386		387		388		389		390		391		392		393	

S.R.I. (386–390) — GT III (391–393)

Profile code | Sender *H.A. de Wit* | Project *SERENGETI PLAIN* | no.

texture

19								
fraction: µm	%	%	%	%	%	%	%	%
>2000								
1000-2000								
500-1000								
250-500								
100-250								
50-100								
2-50								
< 2								

19	classification
	TS : Total Soil

19								
fraction: µm	%	%	%	%	%	%	%	%
1650-2000								
1190-1650								
850-1190								
600-850								
420-600								
300-420								
210-300								
150-210								
105-150								
75-105								
50-75								
32-50								
16-32								
8-16								
4-8								
2-4								
< 2								

elemental analysis

weight percentage: TS < 2 mm; Ba clay < 2 µm

19 / Depths (cm)	80-90		0-9		9-20		20-30		40-50		80-90		110-120		140-150	
SiO_2	44.09	36.28	58.85	44.01	51.50	42.53	52.11	42.69	51.64	41.23	50.68	42.49	53.34	42.82	51.38	36.23
Al_2O_3	11.50	14.98	11.18	17.23	15.70	19.02	16.45	18.83	18.36	18.63	17.13	18.62	17.34	18.55	16.20	15.39
Fe_2O_3 } FeO	6.54	5.60	7.66	9.87	9.07	10.17	8.93	10.03	9.52	9.27	9.16	9.30	9.03	9.01	8.58	7.34
MnO	0.17	0.16	0.46	0.31	0.35	0.21	0.30	0.18	0.21	0.17	0.26	0.17	0.25	0.19	0.18	0.14
MgO	2.28	2.14	1.22	1.10	1.22	1.06	1.38	1.12	1.48	1.13	1.55	1.16	1.78	1.40	2.09	1.56
CaO	14.08	12.05	4.24	0.71	3.10	0.52	2.85	0.52	2.42	0.63	2.60	0.53	2.39	0.50	4.99	0.81
Na_2O	n.d.	0.43	n.d.	0.43	n.d.	0.30	n.d.	0.32	n.d.	0.26	n.d.	0.21	n.d.	0.27	n.d.	0.25
K_2O	4.05	2.59	2.65	2.69	2.87	2.49	2.74	2.47	2.93	2.48	2.99	2.49	3.01	2.45	3.09	2.35
TiO_2	1.84	0.64	2.59	1.70	2.13	1.37	1.92	1.26	1.66	1.00	1.79	1.01	1.72	0.99	1.56	0.94
P_2O_5	1.47	1.27	1.37	1.07	1.02	0.78	0.99	0.71	0.84	0.81	0.79	0.70	0.64	0.73	0.43	0.73
		5.41		3.72		3.71		3.65		4.67		4.42		4.64		14.0
H_2O^+	12.43	18.66	9.15	15.51	10.70	17.51	10.03	17.88	10.52	19.48	9.56	19.21	8.79	18.55	10.42	19.39
Σ	98.45	100.21	99.37	98.35	97.66	99.62	97.70	99.66	99.58	99.76	96.51	100.31	98.34	100.10	98.92	99.13

← GT III → 394 ← 395 396 397 GS III 398 399 400 401 →

39

Profile code Sender *H.A. de Wit* Project *SERENGETI PLAIN* no.

texture

19 fraction: µm	%	%	%	%	%	%	%	%
>2000								
1000-2000								
500-1000								
250-500								
100-250								
50-100								
2-50								
< 2								

19	classification
	TS : Total Soil

19 fraction: µm	%	%	%	%	%	%	%	%
1650-2000								
1190-1650								
850-1190								
600-850								
420-600								
300-420								
210-300								
150-210								
105-150								
75-105								
50-75								
32-50								
16-32								
8-16								
4-8								
2-4								
< 2								

elemental analysis (weight percentage; TS < 2 mm; Ba clay < 2 µm)

19	Depths (cm)	0-10		20-30		40-50		60-70		80-90		110-120		140-150		0-10	
SiO_2		55.08	43.76	54.03	42.91	52.77	41.53	51.68	42.16	54.88	43.81	54.60	43.42	52.58	47.84	49.57	44.07
Al_2O_3		12.34	18.37	14.77	19.42	16.16	19.10	16.17	19.31	16.17	19.38	15.61	18.42	15.34	19.44	14.89	17.34
Fe_2O_3 }	}	7.85	9.92	8.32	10.21	9.05	10.07	9.03	10.05	8.94	10.04	8.60	9.61	8.43	9.81	8.67	9.68
FeO }																	
MnO		0.36	0.21	0.32	0.21	0.31	0.14	0.31	0.15	0.31	0.14	0.31	0.17	0.26	0.22	0.36	0.14
MgO		1.25	1.10	1.23	1.10	1.33	0.95	1.39	0.88	1.36	0.92	1.42	0.98	1.73	1.36	1.58	1.06
CaO		3.79	0.30	3.08	0.43	3.00	0.32	2.89	0.32	2.84	0.26	2.98	0.29	4.56	0.90	2.64	0.30
Na_2O		n.d.	0.27	n.d.	0.28	n.d.	0.26	n.d.	0.30	n.d.	0.29	n.d.	0.26	n.d.	0.39	n.d.	0.41
K_2O		2.59	2.41	2.58	2.40	2.69	2.34	2.68	2.33	2.60	2.34	2.68	2.31	2.88	2.69	2.88	2.78
TiO_2		2.22	1.35	2.02	1.23	2.03	1.16	1.98	1.14	1.97	1.16	1.94	1.15	1.77	1.14	1.76	1.21
P_2O_5		1.26	0.96	1.11	0.86	0.99	0.61	0.88	0.56	0.87	0.50	0.81	0.45	0.77	0.82	0.96	0.64
			4.07		4.09		3.77		3.82		3.78		3.87		4.70		4.01
H_2O^+		12.53	16.83	10.34	16.31	10.50	17.91	10.00	18.12	9.73	17.89	9.20	17.44	10.14	11.03	15.64	17.90
Σ		99.27	99.95	97.85	99.45	98.83	98.17	97.01	99.14	99.67	100.51	98.15	98.37	98.56	100.34	98.95	99.54

← 402 403 404 GL II 405 406 407 408 → ← GV →

Profile code Sender *H.A. de Wit* Project *SERENGETI PLAIN* no.

texture

19									19								
fraction: µm	%	%	%	%	%	%	%	%	fraction: µm	%	%	%	%	%	%	%	%
>2000									1650-2000								
1000-2000									1190-1650								
500-1000									850-1190								
250-500									600-850								
100-250									420-600								
50-100									300-420								
2-50									210-300								
< 2									150-210								
19	classification								105-150								
									75-105								
									50-75								
									32-50								
									16-32								
									8-16								
									4-8								
	TS : Total Soil								2-4								
									< 2								

elemental analysis (weight percentage)

19	TS < 2 mm	< 2 µm Ba clay	20-30		40-50		80-90		128-140		0-25		25-45		45-57.5		70-95	
SiO_2			52.26	43.62	54.26	44.30	54.24	44.17	55.34	45.10	51.26	44.18	51.15	43.13	49.75	43.31	42.68	43.06
Al_2O_3			15.44	17.30	16.13	17.87	16.72	17.49	15.26	17.26	12.61	17.84	14.61	19.80	15.47	20.18	13.58	17.82
Fe_2O_3 / FeO			9.12	9.76	9.17	9.98	9.36	9.71	8.27	8.73	8.47	7.68	9.18	8.37	9.28	8.34	7.22	7.06
MnO			0.42	0.12	0.38	0.13	0.51	0.13	0.29	0.16	0.31	0.18	0.32	0.21	0.32	0.18	0.23	0.24
MgO			1.62	1.06	1.64	1.11	1.75	1.15	1.88	1.24	1.78	1.02	2.04	1.07	2.07	1.05	2.19	1.30
CaO			2.64	0.25	2.59	0.29	2.66	0.30	4.39	0.50	5.58	1.14	5.28	0.95	4.98	0.59	13.50	2.27
Na_2O			n.d.	0.32	n.d.	0.31	n.d.	0.27	n.d.	0.27	n.d.	0.25	n.d.	0.26	n.d.	0.26	n.d.	0.33
K_2O			3.07	2.75	3.10	2.76	3.11	2.73	2.87	2.55	2.46	2.19	2.76	2.40	3.00	2.44	3.18	2.57
TiO_2			1.80	1.24	1.80	1.37	1.74	1.17	1.47	1.09	2.02	0.87	2.14	0.96	2.10	0.93	1.61	0.84
P_2O_5			0.92	0.57	0.86	0.53	0.84	0.52	0.86	0.55	1.71	1.36	1.56	1.16	1.30	0.85	0.90	0.71
				3.99		3.94		3.97		3.92		4.19		4.24		4.38		5.56
H_2O^+			10.33	18.18	9.07	17.89	8.82	18.29	8.29	17.83	12.55	17.43	9.36	17.76	8.91	18.42	13.47	17.99
Σ			97.62	99.16	99.00	100.48	97.75	99.90	98.92	99.20	98.75	98.33	98.40	100.31	97.18	100.93	98.56	99.80

410 411 G.V 412 413 | 414 415 NaNo-A 416 417

Profile code Sender *H.A. de Wit* Project *SERENGETI PLAIN* no.

texture

19									19								
fraction: µm	%	%	%	%	%	%	%	%	fraction: µm	%	%	%	%	%	%	%	%
>2000									1650-2000								
1000-2000									1190-1650								
500-1000									850-1190								
250-500									600-850								
100-250									420-600								
50-100									300-420								
2-50									210-300								
< 2									150-210								
19	classification								105-150								
									75-105								
									50-75								
									32-50								
									16-32								
									8-16								
									4-8								
	TS : Total Soil								2-4								
									< 2								

elemental analysis (weight percentage)

19			120-140		0-20		20-40		50-60		80-100		120-140		0-13		26-40	
	TS < 2 mm	Ba clay < 2 µm																
SiO_2			48.12	39.42	52.44	44.35	50.97	41.55	49.85	42.04	43.29	39.90	44.41	26.73	49.76	43.45	49.44	42.48
Al_2O_3			13.58	14.71	12.82	18.06	14.82	19.05	15.06	19.63	13.58	17.76	12.87	12.21	13.76	17.10	15.54	17.71
Fe_2O_3 / FeO			7.62	5.24	8.46	7.83	9.09	8.14	8.90	8.36	7.42	7.03	7.22	3.58	8.61	9.07	9.03	9.52
MnO			0.23	0.19	0.31	0.18	0.33	0.19	0.32	0.18	0.23	0.24	0.21	0.06	0.34	0.14	0.33	0.16
MgO			2.39	1.41	1.95	1.01	2.03	1.05	2.01	1.07	2.01	1.13	2.50	1.50	1.75	1.17	1.58	1.16
CaO			9.58	1.07	5.72	1.18	5.29	0.88	5.83	0.62	12.80	8.22	12.10	3.73	4.10	0.86	3.41	0.63
Na_2O			n.d.	0.43	n.d.	0.26	n.d.	0.27	n.d.	0.25	n.d.	0.35	n.d.	0.43	n.d.	0.28	n.d.	0.26
K_2O			3.97	2.33	2.52	2.27	2.75	2.33	3.00	2.39	3.12	2.33	3.66	1.44	2.83	2.68	2.95	2.76
TiO_2			1.91	0.72	2.01	0.90	2.09	0.91	2.04	0.94	1.67	0.82	1.84	0.56	1.66	1.11	1.67	1.17
P_2O_5			1.09	0.63	1.81	1.41	1.61	1.06	1.34	0.80	0.91	0.95	0.88	0.39	1.46	1.13	1.14	0.82
BaO				15.5		4.22		4.46		4.14		5.15		27.0		4.23		3.45
H_2O^+			9.57	17.10	11.16	17.04	9.74	17.95	9.67	18.13	13.30	16.08	11.93	17.22	14.76	17.05	12.47	17.27
Σ			98.06	98.80	99.20	98.71	98.72	97.84	98.02	98.55	98.33	99.96	97.62	94.85	99.03	98.27	97.56	97.89
			418		419		420		421		422		423		424		425	
			NaNo-A				NaNo-B								NaNo-S			

Profile code | Sender *H. A. de Wit* | Project *SERENGETI PLAIN* | no.

texture

19									19								
fraction: µm	%	%	%	%	%	%	%	%	fraction: µm	%	%	%	%	%	%	%	%
>2000									1650-2000								
1000-2000									1190-1650								
500-1000									850-1190								
250-500									600-850								
100-250									420-600								
50-100									300-420								
2-50									210-300								
< 2									150-210								
19	classification								105-150								
									75-105								
									50-75								
									32-50								
									16-32								
									8-16								
									4-8								
	T.S : Total soil								2-4								
									< 2								

elemental analysis (weight percentage)

TS < 2 mm; Ba clay < 2 µm

1974	Depths (cm)	55-70		90-114		114-130		0-20		20-37.5		55-75		95-110		130-150	
SiO_2		51.19	44.81	51.37	43.02	47.53	43.89	49.65	43.08	49.76	42.05	51.34	43.76	51.69	45.09	50.15	45.22
Al_2O_3		16.52	18.29	16.66	17.49	15.00	16.73	14.85	18.83	16.22	19.08	16.35	18.16	16.56	18.34	15.86	16.82
Fe_2O_3 } FeO		9.45	9.66	9.50	9.49	8.63	9.01	9.44	9.12	9.74	9.44	9.21	8.96	8.88	8.24	8.88	7.60
MnO		0.34	0.16	0.32	0.15	0.28	0.20	0.34	0.12	0.34	0.20	0.31	0.19	0.30	0.20	0.28	0.27
MgO		1.84	1.21	1.97	1.28	2.22	1.51	1.65	0.98	1.66	0.96	1.64	1.03	1.89	1.07	2.35	1.27
CaO		3.22	0.48	3.37	0.48	7.86	0.85	4.62	0.69	4.18	0.51	4.32	0.59	4.80	0.78	5.37	1.39
Na_2O		n.d.	0.42	n.d.	0.32	n.d.	0.26	n.d.	0.28	n.d.	0.24	n.d.	0.27	n.d.	0.27	n.d.	0.31
K_2O		3.13	2.81	3.15	2.87	3.08	2.91	2.56	2.31	2.70	2.30	2.67	2.17	2.75	2.16	3.15	2.16
TiO_2		1.70	1.20	1.66	1.14	1.46	1.05	2.20	1.05	2.17	1.07	2.00	1.02	1.95	0.94	1.89	0.88
P_2O_5		0.99	0.61	0.99	0.58	0.92	0.68	1.50	0.95	1.26	0.65	1.05	0.62	0.84	0.80	1.03	0.91
BaO			3.98		4.05		4.20		3.85		3.92		4.10		4.86		4.70
H_2O^+		10.29	17.30	10.05	17.40	11.61	17.55	11.91	17.72	10.54	17.73	9.98	17.46	8.84	17.40	8.97	17.00
Σ		98.67	101.01	99.04	98.27	98.54	98.84	98.72	99.08	98.57	98.15	98.87	98.33	98.50	100.15	97.93	98.53
		426		427		428		429		430		431		432		433	

426–428: NaNo-S; 429–433: Na-Lag

Profile code Sender *H. A. de Wit* Project *SERENGETI PLAIN* no.

texture

19								
fraction: µm	%	%	%	%	%	%	%	%
>2000								
1000-2000								
500-1000								
250-500								
100-250								
50-100								
2-50								
< 2								

19	classification
	TS : Total Soil

19								
fraction: µm	%	%	%	%	%	%	%	%
1650-2000								
1190-1650								
850-1190								
600-850								
420-600								
300-420								
210-300								
150-210								
105-150								
75-105								
50-75								
32-50								
16-32								
8-16								
4-8								
2-4								
< 2								

elemental analysis (weight percentage)

1974	*Depths (cm)*	12^5-25		45-60		0-16		30-40		55-70		90-110		130-150		190-210	
	TS < 2 mm / *Ba* < 2 µm *clay*	TS	Ba	TS	Ba	TS	Ba	TS	Ba	TS	Ba	TS	Ba	TS	Ba	TS	Ba
SiO_2		41.30	38.41	38.72	36.66	47.01	43.99	47.51	42.85	47.24	42.05	48.78	42.43	48.78	42.64	49.66	44.41
Al_2O_3		12.65	18.39	12.76	18.32	14.32	18.60	15.01	18.83	15.26	18.98	16.46	19.82	16.07	18.73	17.01	17.16
Fe_2O_3 }	}	9.27	7.71	8.59	7.89	9.23	7.42	9.54	7.65	9.16	7.75	8.95	8.19	8.97	7.97	10.03	8.31
FeO																	
MnO		0.32	0.33	0.28	0.24	0.37	0.25	0.37	0.29	0.37	0.27	0.35	0.30	0.35	0.30	0.35	0.37
MgO		2.54	0.89	2.78	1.36	2.15	1.04	2.26	0.96	2.15	0.98	1.89	1.06	1.97	1.15	2.21	1.44
CaO		12.98	1.57	15.64	0.72	6.47	1.40	6.64	1.52	7.34	1.31	6.12	1.19	6.57	1.08	4.32	0.81
Na_2O		n.d.	0.33	n.d.	0.27	n.d.	0.26	n.d.	0.23	n.d.	0.27	n.d.	0.26	n.d.	0.27	n.d.	0.27
K_2O		2.33	1.53	2.86	1.78	2.59	1.89	2.64	1.89	2.49	1.95	2.66	2.25	2.91	2.29	3.76	2.73
TiO_2		2.22	1.04	1.99	0.83	1.75	0.78	1.87	0.80	1.71	0.83	1.48	0.99	1.47	0.85	1.66	0.91
P_2O_5		1.54	1.44	1.14	0.82	1.69	1.69	1.60	1.52	1.54	1.35	1.29	1.11	1.12	0.98	0.98	0.72
BaO			7.54		11.38		4.81		5.09		4.80		4.80		4.55		4.52
H_2O^+		12.58	18.50	12.47	19.00	13.69	17.61	11.30	17.26	11.96	17.56	11.37	17.57	10.65	17.14	8.00	16.75
Σ		98.23	97.66	97.25	99.17	99.27	99.74	98.74	98.89	99.22	98.10	99.40	99.97	98.86	97.95	97.98	98.40
		434		435		436		437		438		439		440		441	

← BARSEK → ← SEK-NE →

Percentages of heavy minerals in sand fraction (50-420 μm)

Profile, depths (cm)		sample number	% (weight) heavy minerals	weight (g) of fraction 50-420 μm
SRI III	0-15	386	5.58	6.1093
	15-32	387	4.61	5.5690
	92-105	390	4.76	2.2816
GT III	0-10	391	32.08	3.6662
	80-90	394	29.23	3.9867
GS III	0- 9	395	29.67	3.3076
	20-30	397	27.78	1.6365
	140-150	401	19.95	1.3466
G.L.II	0-10	402	32.61	2.7144
	20-30	403	29.40	2.0632
	140-150	408	19.21	1.1767
G.V.	0-10	409	27.70	0.5376
	128-140	413	23.32	0.8237
NaNo-A	0-25	414	57.17	1.5490
	45-57.5	416	55.00	1.6769
	120-140	418	27.22	2.3310
NaNo-B	0-20	419	56.80	1.6411
	120-140	423	40.42	2.3085
NaNo-S	0-13	424	43.15	1.0706
	114-130	428	29.32	1.2511
Na-Lag	0-20	429	58.25	2.1392
	130-150	433	30.24	2.3781
SEK-NE	0-16	436	39.68	2.6651
	55-70	438	42.51	2.2876
	190-210	441	39.36	1.0989

Appendix 47

(Derived from Braun,1972)

Presence percentage of grasses and Cyperaceae in three grassland zones; quadrats of 1 hectare.

species name (abbreviation)	species name	Short (102[1])	Intermediate (108[1])	Long (194[1])	growth[2]) habit
Cyda	Cynodon dactylon (L.)Pers.	97%	99%	93%	S, P
Miku	Microchloa kunthii Desv.	94	95	94	T, P
Dima	Digitaria macroblephara(Hack.) Stapf	88	96	98	T, P
Hars	Harpachne schimperi A.Rich.	86	72	59	T, P
Sfim	Sporobolus fimbriatus Nees	93	69	39	T, P
Eupa	Eustachys paspaloides(Vahl) Lanza & Mattei	83	76	30	T-R, P
Disc	Digitaria scalarum(Schweinf.) Chiov.	88	51	19	R, P
Smar	Sporobolus marginatus A.Rich.	94	9	2	S/T, P
Kyllnerv	Kyllinga nervosa Steud.	98	8	1	T, P
Erau	Eragrostis aulacosperma(Fresen.) Steud.	84	6	1	T, P
Sver	Sporobolus verdcourtii Napper	66	6	2	S, P
Orca	Oropetium capense Stapf	52	-	4	T, P
Cypl	Cynodon plectostachyus(K.Schum., Pilg.)	42	1	6	S, P
Shom	Sporobolus homblei De Wild.	30	-	-	T, P
Spic	Sporobolus spicatus(Vahl) Kunth	26	2	1	S, P
Bsem	Brachiaria semiundulata(A.Rich.) Stapf	3	42	21	A
Dite	Digitaria ternata(A.Rich.)Stapf	3	31	17	T, A
Erio	Eriochloa nubica(Steud.)Thell.	11	33	21	T, A
Spel	Sporobolus pellucidus Hochst.	13	51	19	T, P
Agre	Andropogon greenwayi Napper	4	95	2	S, P
Erte	Eragrostis tenuifolia(A.Rich.) Steud.	7	85	41	T, A/P?
Patr	Panicum atrosanguineum A.Rich.	42	82	29	T, P
Cpyc	Chloris pycnothrix Trin.	77	96	52	A
Erci	Eragrostis cilianensis(All.) Lutati	39	82	58	T, A
Pest	Pennisetum stramineum Peter	5	86	62	T, P
Peme	Pennisetum mezianum Leeke	23	85	98	R(T), P
Ttri	Themeda triandra Forsk.	18	63	92	T, P
Arke	Aristida keniensis Henr.	26	50	75	A
Stap	Sporobolus stapfianus Gandoger & S.festivus A.Rich.	-	15	72	T, P
Arad	Aristida adoënsis Hochst.	-	7	59	T, P
Boin	Bothrichloa insculpta(A.Rich.) A.Camus	1	10	43	T-S, P

species name (abbreviation)	species name	Short	Intermediate	Long	growth[2]) habit
Cyperasp	Cyperaceae species	16	18	35	
Cyex	Cymbopogon excavatus(Hochst.) Stapf	-	-	25	T, P
Paco	Panicum coloratum L.var.Zeko	7	4	4	R/S, P
Enel	Enneapogon elegans(Nees) Stapf	3	4	9	T, P
Slon	Sporobolus longibrachiatus Stapf	22	15	-	T, P
Trab	Tragus berteronianus Schult.	21	11	8	T, A
Ceci	Cenchrus ciliaris L.	14	4	2	T-R, P
Elsp	Eleusine species (Gaertn.)	21	-	-	T-R, P
Urog	Urochloa geniculata C.E.Hubbard	3	10	6	A
Beru	Brachiaria eruciformis(J.E.Sm.) Griseb.	-	13	8	T, A
Sepa	Setaria pallidifusca (Schumach.) Stapf & C.E.Hubbard	1	19	23	A
Paco	Panicum coloratum L.	1	7	18	T, P
Smar	Sporobolus marginatus var.Kiem.	-	1	15	S, P
Chry	Chrysochloa orientalis(C.E.Hubbard)-Swallen	-	-	8	S/T, P
Spha	Setaria sphacelata Stapf et C.E. Hubbard	-	1	7	(R)-T, P
Daeg	Dactyloctenium aegyptium(L.) Beauv.	3	3	13	T, A
Bpub	Brachiaria pubifolia Stapf	-	-	7	

Other grasses that are locally common (e.g. on Miscellaneous landtypes):

Scon	Sporobolus consimilis Fresen.	T (-R)P
Cgay	Chloris gayana Kunth	S, P
Odja	Odyssea jaegeri (Pilg.) Robyns & Tournay Syn. for Psilolemma jaegeri (Pilg.) S.M.Philips	S, P
Heco	Heteropogon contortus (L.) P.Beauv.ex Roem.& Schult.	T, P
Pama	Panicum maximum Jacq.	T-R, P

1) number of quadrats

2) T= Tufted, S= Stoloniferous, R= Rhizomatous, P= Perennial, A= Annual
/= or, -= and.

Presence percentage of herbs in three grassland zones; quadrats of 1 hectare.

species name (abbreviation)	species name	Short (102[1])	Intermediate (108[1])	Long (183[1])
Euphinae	Euphorbia inaequilatera Sond.	94	77	49
Leuneufl	Leucas neufliseana Courb.	96	15	15
Melhovat	Melhania ovata (Cav.) Spreng.	85	5	-
Asterhys	Aster hyssopifolius Berg.	71	24	8
Phyllasp	Phyllanthus aspericaulis Pax	60	1	1
Medlacin	Medicago laciniata (L.) Mill.	57	17	3
Indmicro	Indigofera microcharoides Taub.	56	3	2
Rhampheu	Rhamphicarpa heuglini Hochst.	56	20	19
Craterpl	Craterostigma plantagineum Hochst.	37	8	8
Iplongit	Ipomoea longituba Hall.f.	25	-	-
Plumonoc	Pluchea monocephala E.A.Bruce	25	2	1
Crotrhiz	Crotolaria rhizoclada Polhill	34	25	1
Hirpdiff	Hirpicium diffusum (O.Hoffm.) Roess.	53	11	25
Solincan	Solanum incanum L.	78	93	70
Justexig	Justicia exigua S.Moore	61	88	73
Sidovata	Sida ovata Forsk.	29	70	58
(Monsangu)	Monsonia biflora DC.(=M.angustifolia E.Mey.)	29	56	22
Crotspin	Crotalaria spinosa Benth.	3	88	73
Indbasif	Indigofera basiflora Gillet.	4	57	26
Indvolke	Indigofera volkensii Taub.	9	47	42
Cucurbsp	Cucurbitaceae species	-	30	27
Helisteu	Heliotropium steudneri Vatke	2	72	21
Asyschim	Asystasia schimperi T.Anders.	19	37	4
Pentoura	Pentanisia ouranogyne S.Moore	1	37	9
Enicohys	Enicostemma hyssopifolium (Willd.) Verdoorn	18	34	19
Rhyndens	Rhynchosia densiflora (Roth) DC.	2	28	20
Justelli	Justicia elliotii S.Moore	-	25	4
Dyschora	Dyschoriste radicans Nees in DC.	3	23	53
Leubract	Leucas bracteosa Guerke	-	33	54
Indhochs	Indigofera hochstetteri Bak.	4	14	37
Sidcunei	Sida cuneifolia Roxb.B.	1	17	26
Heliglum	Helichrysum glumaceum DC.	65	46	16
Beciumsp	Becium species	59	38	6
Hypofors	Hypoestes forskalei (Vahl)R.Br.	10	6	1
Polygasp	Polygala species	3	4	3
Leumicro	Leucas microphylla Vatke	-	-	5
Hermuhli	Hermannia uhligii Engl.	-	1	11

[1]) number of quadrats

ecies name (abbreviation)	species name	Short	Intermediate	Long
Andromel	Androcymbium melanthioides Willd.	12	11	-
Heliundu	Heliotropium undulatifolium Turrill	16	6	14
Indmasai	Indigofera masaiensis Gillet	7	4	-
Oldwiede	Oldenlandia wiedemannii K.Schum.	12	8	-
Tribterr	Tribulis terrestris L.	8	7	5
Lepidafr	Lepidium africanum (Burm.f.) DC.	13	1	3
Liliaspe	Liliaceae species	15	10	10
Amargrae	Amaranthus graecizans L.	10	6	4
Erucarab	Erucastrum arabicum Fisch.et Mey.	17	11	3
Casfalci	Cassia falcinella Oliv.	-	15	13
Crambaby	Crambe abyssinica Hochst.ex R.E.Fries	6	16	1
Indbogda	Indigofera bogdanii Gillet	-	21	5
Leumarti	Leucas martinicensis R.Br.	8	14	1
Privacur	Priva curtisiae Kobuski	1	21	7
Zaleypen	Zaleya pentandra (L.) Jeffrey	-	20	18
Sonchusp	Sonchus species	-	11	7
Commicsp	Commicarpus species	-	6	2
Achyrasp	Achyranthes aspera L.	-	2	6
Commtril	Commelina trilobosperma K.Schum.e desc.	-	5	13
Commelsp	Commelina species	4	13	24
Crotdese	Crotalaria deserticola Bak.f.	-	4	17
Crotbrev	Crotalaria brevidens Benth.	-	-	5
Cyathort	Cyathula orthacantha (Hochst.)Schinz	-	4	21
Emicocci	Emilea coccinea (Sims) Sweet	-	1	11
Gutpeter	Gutenbergia petersii Steetz	-	20	22
Hibflavi	Hibiscus flavifolius Ulbr.	-	6	21
(Ipjaeger)	Ipomoea L. species(jaegeri Pilg.?)	6	16	17
Glywight	Glycine wightii (Wight & Arn.)Verdc.	-	6	10
Neocalte	Neocentema alternifolia (Schinz)Schinz	-	3	14
Orthopar	Orthosiphon parvifolius Vatke	-	-	6
Soldubiu	Solanum dubium Fresen.	-	2	11
Talcaffr	Talinum caffrum (Thunb.) Eck.& Zey.	-	-	8
Tephpumi	Tephrosia pumila (Lam.) Pers.	-	1	14
Crotvall	Crotalaria vallicola Bak.f.	-	2	8
Sencoron	Senecio coronopifolius Desf.	-	1	7
Tephrosp	Tephrosia Pers. species	-	5	8
Blephaca	Blepharis acanthodioides Klotzsch	-	2	8

Species name (abbreviation)	species name	Short	Intermediate	Long
Crotsere	Crotalaria serengetiana Polhill	12	8	16
Gutfisch	Gutenbergia fischeri R.E.Fries	4	-	2
Habepipa	Habenaria epipactidea Reichb.f.	1	12	1
Portquad	Portulaca quadrifida L.	3	18	17
Rhynmini	Rhynchosia minima (L.) DC.	1	7	15
Abutilsp	Abutilon species	6	5	5
Casgrant	Cassia grantii Oliv.	-	4	15
Ophiospe	Ophioglossum species	7	4	2

List of trees and shrubs, occurring near the fringes of the Serengeti Plain and on Miscellaneous land types (kopjes, dunes, deeply incised valleys, riverbeds):

Acacia albida Del.
Acacia clavigera E.Mey.
Acacia drepanolobium (Harms ex) Sjöstedt
Acacia mellifera (Vahl) Benth.
Acacia senegal (L.) Willd.
Acacia sieberiana DC.
Acacia tortilis (Forsk.) Hayne
Albizia harveyi Fourn.
Ballanites aegyptiaca (L.) Del.
Commiphora madagascariensis Jacq.
Commiphora trothae Engl.
Euphorbia candelabrum Kotschy
Ficus sp.
Kigelia africana (Lam.) Benth.
Phoenix reclinata Jacq.
Aloe volkensii Engl.
Aspilia mossambicensis (Oliv.) Willd.
Grewia fallax K.Schum.
Grewia trichocarpa A.Rich.
Hoslundia opposita Vahl
Maerua triphylla A.Rich.
Sansevieria ehrenbergiana Schweinf.

Curriculum vitae

De auteur werd op 18 maart 1941 geboren te Utrecht. Na het behalen van het diploma Gymnasium-B aan het Marnix College te Ede ging hij in 1960 studeren aan de Landbouwhogeschool te Wageningen. Na zijn praktijktijd in Centraal Anatolië (Turkije) in het kader van het Konya Project van de Landbouwhogeschool werd in 1967 het kandidaatsexamen in de Bodemkunde en Bemestingsleer afgelegd. In 1970 werd het ingenieursexamen in de Tropische Bodemkunde afgelegd, met als hoofdvak de Tropische Bodemkunde (verzwaard), als eerste keuzevak de Algemene Bodemkunde en Bemestingsleer en als tweede keuzevak de Plantengeografie van Subtropische en Tropische gebieden.
Van 1970 tot 1974 stelde de Stichting voor Wetenschappelijk Onderzoek van de Tropen (WOTRO) hem in staat een onderzoek te verrichten naar de relaties tussen graslandvegetatie en bodemgesteldheid in het Serengeti National Park in Tanzania. Gedurende deze periode was hij als wetenschappelijk ambtenaar werkzaam bij het Serengeti Research Institute. Van 1976 to 1977 was hij werkzaam bij de vakgroep Bodemkunde en Geologie van de Landbouwhogeschool in het kader van de TAP-regeling.